Renewable and Sustainable Energy Reviews 40 (2014) 386–399

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Evaluation of the different aerodynamic databases for vertical axis wind turbine simulations

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ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form
26 May 2014
Accepted 18 July 2014
Available online 15 August 2014

Keywords:
Vertical axis wind turbine
Aerodynamic coefficients
Blade Element-Momentum algorithm
Experimental data

ABSTRACT

A review on a wide number of different aerodynamic coefficient databases to be used for vertical axis wind turbine simulations is conducted in this work. The databases are adopted in conjunction with a Blade Element-Momentum algorithm, a commonly used tool to design and verify the aerodynamic behaviour of these machines. Experimental data derived from field test available in the literature for a wide range of rotor sizes are considered and compared to the simulation results. The aerodynamic databases provide strongly different estimations due to the different working conditions: in each case suggestions on their use are provided based on their reliability. Finally, resuming all the conducted validations, practical general considerations are proposed to the wind turbine designer to conduct reliable simulations.

Contents

1. Introduction

Vertical axis wind turbines are recently gaining a considerable interest due to their inherent qualities that make their use with respect to the horizontal axis systems. The design simplicity linked to the bottom position of the generator and combined with the easiest control policy, which does not require any pitch or yaw mechanism, allows their use in both urban and extremely isolated areas, where the maintenance work needs to be minimized. On the other hand, these machines are characterized by a complex aerodynamics due to the peculiar unsteady working conditions. A flexible and reliable design tool is thereby needed, which should be preventively validated against experimental data.

In the past years, a considerable amount of papers has been developed on experimental activities for Darrieus rotor of different sizes and characteristics. Sandia National Laboratories provided experimental data from both wind tunnel and open field tests for rotors with a height of 2 m [1], 5 m [2] and 17 m [3,4]. Turbines with even greater size have been tested in open field environment: the most important examples are the 37 m height Darrieus installed on Magdalen Islands [5,6], for a maximum power production of 230 kW, and the biggest Darrieus ever realized, the Éole project with a height of 96 m and a power production of 4 MW [7]. These turbines operate at different Reynolds numbers, due to their different sizes, and are characterized by different solidities and aerodynamic profiles, mainly NACA 0012, NACA 0015 and NACA 0018. All these experimental data provide a good background for the validation of numerical models, which are needed in order to conduct a successful design activity.

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http://dx.doi.org/10.1016/j.rser.2014.07.126
1364-0321/

Nomenclature

a (−) axial induction factor
a_u (−) upwind axial induction factor
ΔA (m^2) streamtube cross-sectional area
A_S (m^2) rotor swept area
c (m) airfoil chord
C_D (−) airfoil drag coefficient
C_L (−) airfoil lift coefficient
C_N (−) blade element normal coefficient
C_P (−) rotor power coefficient
C_T (−) blade element tangential coefficient
ΔF_N (N) normal force exerted by the blade element as it passes through the streamtube
ΔF_T (N) tangential force exerted by the blade element as it passes through the streamtube
ΔF_x (N) instantaneous streamwise force exerted by the blade element as it passes through the streamtube
$\Delta F_{x,u}$ (N) instantaneous streamwise force exerted by the blade element as it passes through the upwind streamtube
$\Delta \overline{F}_{x,u}$ (N) average streamwise force exerted by the blade element as it passes through the upwind streamtube
G_u (−) auxiliary function for induction factor iterative algorithm
H (m) rotor total height
N (−) number of blades
N_θ (−) number of horizontal mesh subdivisions
N_v(−) number of vertical mesh subdivisions
P(W) power produced by the turbine
p_u^+ (Pa) pressures on the upstream face of the upwind actuator disc
p_u^- (Pa) pressures on the downstream face of the upwind actuator disc
r (m) rotor radius relative to a blade element
R (m) wind turbine maximum radius
T (N m) rotor torque
V (m/s) freestream wind speed
V_e (m/s) downstream equilibrium wind speed
V_i (m/s) flow velocity at a blade section, i can be up or down
V_u (m/s) flow velocity at the downwind blade section
W_i (m/s) relative velocity at a blade element cross-sectional plane, i can be up or down
W_u (m/s) relative velocity at the upwind blade element cross-sectional plane
Δz (m) streamtube height
α (rad) blade relative angle of attack (between airfoil chord line and relative wind velocity)
δ (rad) blade element inclination with respect to the vertical plane
λ (−) tip speed ratio
ρ (kg/m^3) air density
θ (rad) blade azimuthal coordinate
$\Delta\theta$ (rad) azimuthal mesh size
ω (rad/s) rotor angular velocity

Different numerical models for the simulation of the complex aerodynamics of these machines have been developed. Three main approaches have been followed, subsequentially developed with the advent of more powerful computational resources. The first model is the Blade Element-Momentum (BE-M) Multiple Streamtube developed by Strickland [8], successively improved by Paraschivoiu [9,10] considering the Double Disc approach. This model has the advantage of being extremely light and fast to provide an estimation of the whole power curve and off-design production, but on the other hand the result reliability is strongly dependent on the quality and the extension of the aerodynamic database adopted. An improved description for the Darrieus wake was possible by the Vortex Wake model developed by Strickland [11], which is able to provide an additional insight of the aerodynamic behaviour. On the other hand, the computational time required for the simulation is sensibly increased with respect to the previously mentioned method. Finally, Computational Fluid Dynamics (CFD) codes provide the most accurate description for turbine aerodynamics [12,13] but, on the other hand, require more computational time, limiting their use for final testing simulations more than design activities.

The BE-M code is considered by the authors to be the most suitable code for design purposes. The choice is linked to the simplicity of the algorithm formulation along with the small computational time required. These peculiarities allow its adoption even coupled with optimization algorithms for the automatic design improvement, which may require a considerable number of rotor performance evaluations. As stated before, the reliability of this method is strongly dependent on the accuracy of the aerodynamic database adopted. The simulation of vertical axis rotors requires aerodynamic coefficients extended from angles of attack between -180° and $+180^\circ$ covering a large span of Reynolds number. Unfortunately, the literature review provides mainly experimental databases developed for aeronautic applications, which are very limited in angles of attack and Reynolds numbers. In this work, the main databases available in the literature are considered and the results obtained were compared, in order to provide the vertical axis turbine researchers with a practical indication on the methodology to apply for their studies. The databases considered are the one from Sheldahl et al. [14] and their derivatives from Paraschivoiu [15] and Lazauskas et al. [16]. In addition to these, databases from Jacobs et al. [17,18], Bullivant [19] and Gregorek at al. [20], obtained for aeronautic applications, have been extended beyond stall and included in the comparison. A complete description of these databases is reported in the technical report from Bedon et al. [21].

2. Simulation model

The simulation model hereby adopted is based on the Double Multiple Streamtube approach developed by Strickland [8] and Paraschivoiu [9,10]. Two actuator discs describe the upwind and downwind rotor sections, where the induction factors are calculated. The induction factor represents the decrease of air velocity from the freestream due to the interaction with the blade and is defined as

$$a = 1 - \frac{V_i}{V} \quad (1)$$

where V_i is the velocity at the blade (upwind or downwind section) and V is the freestream air speed. The induction factor is estimated equating the streamwise forces on the airfoil blades to the change in fluid momentum. The first forces can be estimated considering that the actuator disc extracts energy from the fluid and therefore generates a pressure jump which, for the upwind section, can be calculated as

$$\Delta \overline{F}_{x,u} = (p_u^+ - p_u^-)\Delta A \quad (2)$$

where p_u^+ and p_u^- are respectively the pressures on the upstream and downstream faces of the upwind actuator disc and ΔA is the streamtube cross-sectional area.

By considering Bernoulli's equation first between the upstream equilibrium station and the actuator disc and second between the actuator disc and the downstream equilibrium, Eq. (2) becomes

$$\Delta\overline{F}_{x,u} = \frac{1}{2}\rho(V^2 - V_e^2)\Delta A \tag{3}$$

where ρ is the air density and V_e is the downstream equilibrium wind speed.

The streamwise force must be also equal to change in the fluid momentum, in formula

$$\Delta\overline{F}_{x,u} = (\rho V_u \Delta A)(V - V_e) \tag{4}$$

where V_u is the local wind speed.

By comparing Eqs. (3) and (4), the following relation is obtained:

$$V_e = 2V_u - V \tag{5}$$

Considering the streamtube area as

$$\Delta A = r\Delta\theta\Delta z \cos\theta \tag{6}$$

where r is the blade element radius, $\Delta\theta$ is the azimuthal mesh size, Δz is the height mesh size and θ is the azimuthal position, Eq. (4) combined with (5) becomes

$$\Delta\overline{F}_{x,u} = 2\rho r\Delta\theta\Delta z \cos\theta V_u(V - V_u) \tag{7}$$

The blade can be also seen as the responsible for the loads. The instantaneous streamwise force on the element can be therefore expressed as

$$\Delta F_x = \Delta F_N \cos\delta \cos\theta + \Delta F_T \sin\theta \tag{8}$$

where ΔF_N and ΔF_T are respectively the normal and tangential forces and δ is the blade local slope.

By introducing the normal and the tangential force coefficients, C_N and C_T, Eq. (8) becomes

$$\Delta F_{x,u} = \frac{1}{2}\rho W_u^2 \left(\frac{c\Delta z}{\cos\delta}\right)[C_N \cos\delta \cos\theta + C_T \sin\theta] \tag{9}$$

where W_u is the relative local wind speed at the upwind blade position and c is the blade chord.

The average streamwise force for the upwind section can be found by averaging the consecutive instantaneous force values at different azimuthal positions and multiplying by the number of blades:

$$\Delta\overline{F}_{x,u} = \rho W_u^2 \left(\frac{N\Delta\theta}{4\pi}\right)\left(\frac{c\Delta z}{\cos\delta}\right)[C_N \cos\delta \cos\theta + C_T \sin\theta] \tag{10}$$

where N is the number of blades. The normal and tangential force coefficients are commonly derived from the airfoil aerodynamic coefficients, in formulas

$$C_N = C_L \cos\alpha + C_D \sin\alpha \tag{11}$$

$$C_T = C_L \sin\alpha - C_D \cos\alpha \tag{12}$$

where C_L and C_D are respectively the lift and drag lift coefficients and α is the geometrical angle of attack.

An induction factor is initially assumed and the algorithm is iterated. A convenient formulation in order to obtain a reliable convergence is suggested by Homicz [22], who provides a function to compute the induction factor for the new iteration:

$$a_u = \frac{1}{1 + G_u(a_u)} \tag{13}$$

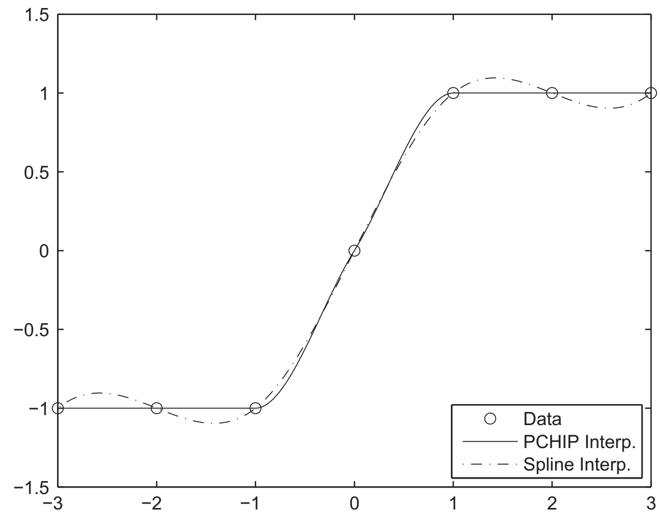

Fig. 1. Different interpolation smoothness with respect to PCHIP and Spline methods [30].

with the function G_u expressed as

$$G_u(a_u) = \frac{Nc}{8\pi r \cos\theta}\left[C_N \cos\theta + C_T\frac{\sin\theta}{\cos\delta}\right]\left(\frac{W_u}{V_u}\right)^2 \tag{14}$$

A similar formulation can be derived for the downwind section, giving a second induction factor. As can be clearly seen, the aerodynamic coefficients are deeply involved in the iterative solution for the performance estimation and a particular attention should be given to their choice. In particular, Reynolds number experiences a wide change during one revolution and for different operative conditions due to the different relative wind speeds. In order to obtain the most reliable estimation from the aerodynamic database, an interpolation on the angle of attack and on the selected Reynolds number is adopted. The selected interpolation algorithm is the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) [23], which allows a smoother interpolation than other interpolation algorithms e.g. spline interpolation, as can be seen in Fig. 1, and is suggested for these types of applications [24].

Different authors provide also models derived from aeronautical use for the dynamic stall evaluation. The blade experiencing a cyclic change in angle of attack shows aerodynamic coefficients different from the static values particularly beyond stall [15,25,26]. The effect is important for operative conditions characterized by low tip speed ratios but, in this work, in order to obtain the clearest comparison possible, additional models were not included.

From the tangential coefficient C_T the aerodynamic rotor torque can be estimated by means of

$$T = \frac{N}{N_\theta}\sum_1^{N_\theta}\sum_1^{N_V}\left(0.5\rho r C_T \frac{c\Delta z}{\cos\delta}\right)W_i^2 \tag{15}$$

where N_θ and N_V are respectively the number of azimuthal and vertical mesh elements and W_i is the relative wind speed (upwind or downwind section).

Finally, the power production and the power coefficient are defined as

$$P = T\omega \tag{16}$$

$$C_P = \frac{P}{0.5\rho U_\infty^3 A_S} \tag{17}$$

with ω being the rotational speed and A_S being the rotor swept area.

3. Aerodynamic databases

Sheldahl: A very diffused and adopted database for BE-M simulations of vertical axis wind turbine is the one provided by Sheldahl et al. [14]. The database is experimentally obtained for three profiles NACA 0009, 0012 and 0015 at three Reynolds numbers 3.5×10^5, 5.0×10^5 and 7.0×10^5, respectively. The database is successively expanded by means of numerical algorithms for NACA 0018, 0021 and 0025 and a wider range of Reynolds numbers. This range includes also very low Reynolds numbers which often characterize the flow in a vertical axis wind turbine. The lift coefficient for NACA 0012 at low Reynolds numbers is represented in Fig. 2.

The graph highlights peculiarities for this database which must be kept in consideration for the following simulation results. The airfoil at stall conditions presents a very steep decrease in the lift coefficient, which reaches the lower value by increasing the angle of attack of 1° or 2° from the maximum lift coefficient. This is linked to the thin nature of the airfoil, which incurs in an abrupt stall, but this extreme predicted behaviour could be also linked to the nature of the numerical algorithm adopted to obtain these coefficients. Moreover the lift coefficient for the Reynolds numbers lower than 1.6×10^5 presents a negative value at certain angles of attack, which sounds counter-intuitive considering the similarities with a flat plate. For this reason, in the following computations, only the data for Reynolds number higher than 1.6×10^5 are considered.

Furthermore it is possible to observe that for angle of attack greater than 30° the lift coefficients for all the Reynolds numbers and all the profiles are the same but for the NACA 0012, which however presents only small changes. This is shown in Fig. 3.

The decrease in the lift coefficient after the stall is less steep for the thicker profiles and the whole behaviour is smoother. On the other hand, it is possible to observe that after 30° a jump in almost all the lift coefficients is present: the numerical algorithm provided the same values for all the profiles and therefore the switch between the databases is not smooth.

Paraschivoiu: The second database considered is the one provided by Paraschivoiu [15]. The database is obtained for NACA 0012, 0015 and 0018 and Reynolds numbers between 10^4 and 10^7. The database is very similar to the previous one but it is provided with aerodynamic coefficients for a larger number of angles of attack, probably obtained through a different interpolation than the one adopted in this work. The difference between the interpolated database from Sheldahl and the one proposed by Paraschivoiu is depicted in Fig. 4 for the lift coefficient of NACA 0018 at a Reynolds number of 1.6×10^5.

The difference in lift coefficient varies considering different airfoil thicknesses: it is lower than 1% for NACA 0012 and NACA 0015 but it reaches values up to 7.9% for NACA 0018 at Reynolds number of 7×10^5. Moreover the maximum differences in drag coefficient for NACA 0015 and NACA 0018 are respectively 1.2% and 2.2% at Reynolds numbers of 1.6×10^5 and 3.6×10^5. This difference could be argued to be limited but, on the other hand, the vertical axis wind turbines operate in this range of angles of attack and therefore a slight difference could not be preventively omitted. In order to enhance the difference in databases, for this

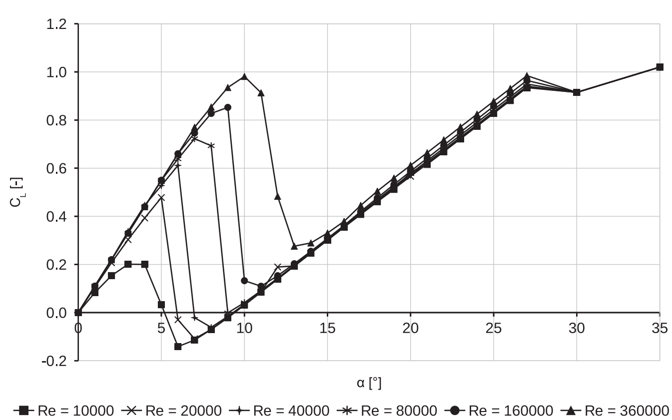

Fig. 2. Aerodynamic lift coefficient for NACA 0012 at low Reynolds numbers, Sheldahl et al. [14].

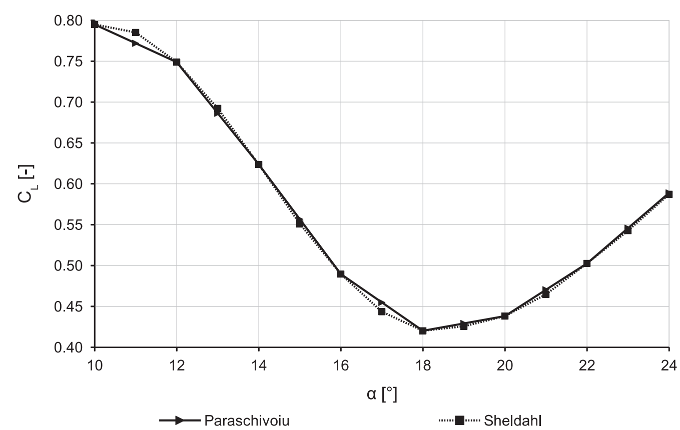

Fig. 4. Difference in lift coefficients between Paraschivoiu and interpolated Sheldahl database for NACA 0018 and Reynolds number of 1.6×10^5.

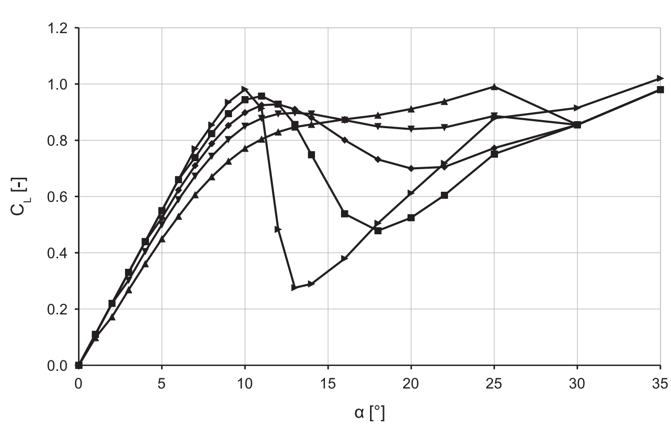

Fig. 3. Aerodynamic lift coefficient for different NACA symmetric profiles at a Reynolds number of 3.6×10^5, Sheldahl et al. [14].

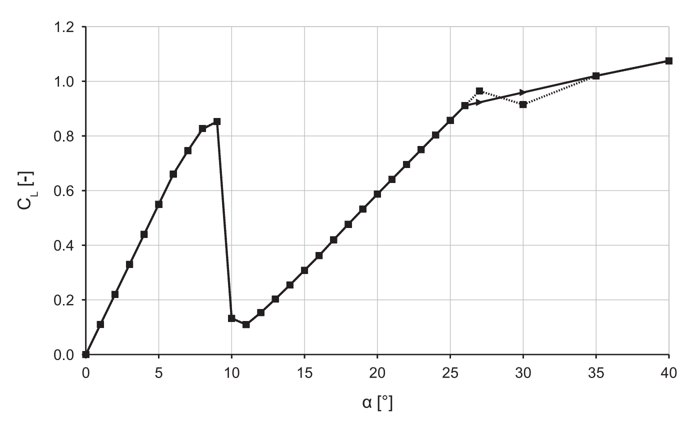

Fig. 5. Difference in lift coefficients between Lazauskas and interpolated Sheldahl database for NACA 0012 and Reynolds number of 1.6×10^5.

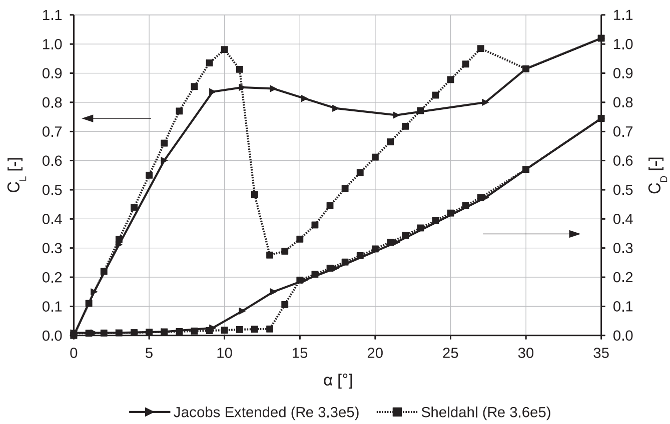

Fig. 6. Extended Jacobs database compared against Shedahl for NACA 0012.

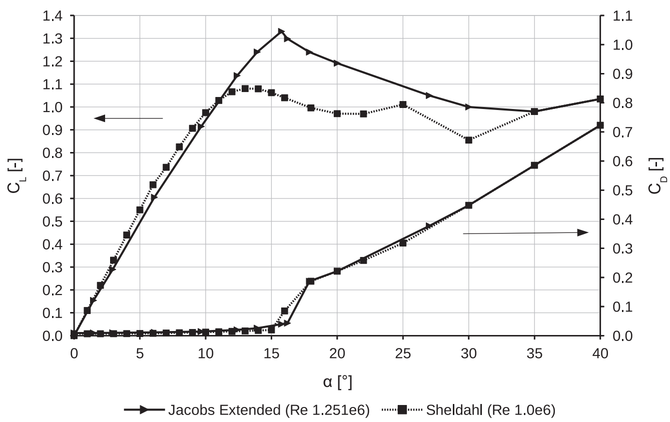

Fig. 7. Extended Jacobs database compared against Shedahl for NACA 0018.

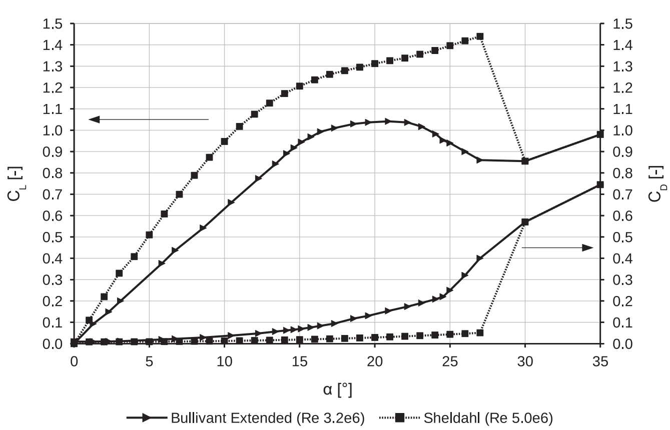

Fig. 8. Extended Bullivant database compared against Shedahl for NACA 0025.

computations all the Reynolds numbers are considered, even those for which a negative lift coefficient at some angles of attack is present.

Lazauskas: The third considered database is again based on the Sheldahl database but it has been modified by Lazauskas et al. in order to correct the glaring anomalies [16]. As previously observed, indeed, the switch between the experimental data and the numerical prediction in the Sheldahl database created a "jump" in the lift coefficient data. Lazauskas et al. corrected these values in order to provide a smoother trend, as shown in Fig. 5 for the NACA 0012 profile at a Reynolds number of 1.6×10^5.

Sheldahl, Paraschivoiu and Lazauskas databases represent the most famous databases available in the literature whose angles of attack are extended between -180° and $+180^\circ$, allowing their

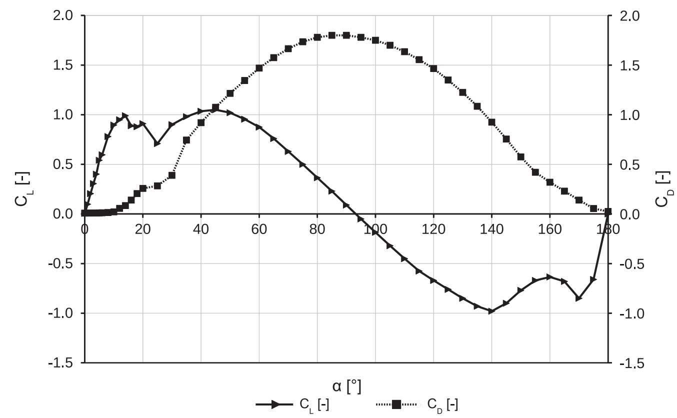

Fig. 9. Extended Gregorek database for SNLA 0018-50, average Reynolds number of 1.41×10^6.

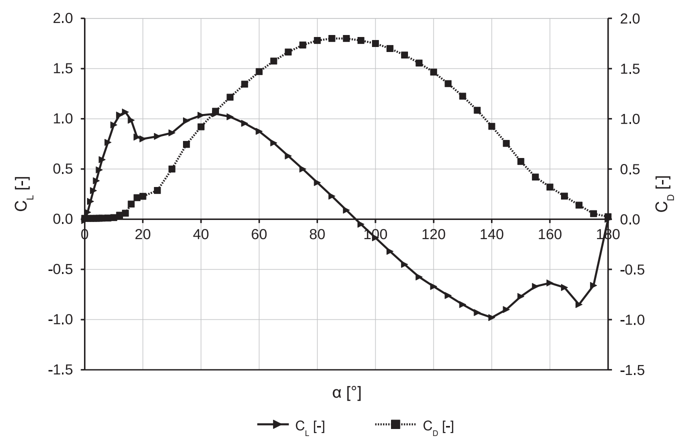

Fig. 10. Extended Gregorek database for SNLA 0018-50, average Reynolds number of 2.52×10^6.

direct use for vertical axis wind turbine applications. However, a few amount of other authors provided the results for airfoil experimental test even at low Reynolds number on the same profiles, but with a limited range of angles of attack. The airfoils in vertical axis wind turbines operate with angles of attack lower than 30° in most of the azimuthal and vertical positions, so it is reasonable to assume that numerically extending the limited databases to higher angles of attack would lead to prediction not largely affected by errors.

Jacobs: Jacobs et al. [17,18] provided experimental databases for NACA 0009, 0012, 0015, 0018 and 0021 and Reynolds numbers ranging between approximately 1.6×10^5 and 3×10^6. The aerodynamic coefficients are provided for a maximum angle of attack of 28°. In order to overcome this limitation, the Sheldahl database is considered: the aerodynamic coefficients for higher angles of attack are included in order to create a complete database. However, in order to provide a smooth transition between the database and the extension, in a region comprised between $\pm 2^\circ$ from the switch point, the database coefficients are replaced with interpolated values. The extended databases for NACA 0012 and NACA 0018 at Reynolds number around 3.6×10^5 and 1×10^6 are shown in Figs. 6 and 7, respectively, compared against the nearest database from Sheldahl.

A considerable difference is highlighted between the lift coefficient trends. The lift coefficient proposed by Jacobs highlights an initial linearity similar to Shedahl's one. On the other hand, Sheldahl lift coefficients are characterized by a steeper and earlier stall conditions, where the values are sensibly decreased from the maximum lift. Moreover, Jacobs maximum lift values are higher than Sheldahl's one for high Reynolds number and thick profiles. Jacobs drag coefficients are instead generally similar to the Sheldahl values.

Bullivant: Jacobs et al. [17,18] do not include any data for NACA 0025 profiles. One of the few databases available in the literature is provided by Bullivant [19] for the only Reynolds number of 3.2×10^6. Again, the database is provided only for angles of attack lower than 25° and it is therefore extended including the data from Sheldahl database and substituting the coefficients next to the switch point with the interpolated values in order to provide a smooth transition as for the previous database. The comparison between the Bullivant and the Shedahl database is reported in Fig. 8.

Both the lift and drag coefficients from Bullivant database appear to be smoother than the Sheldahl values, which present a considerable jump linked to the change in methodology (experimental/numerical). Bullivant maximum lift coefficient is also lower and, consequently, characterized by a higher drag coefficient.

Gregorek: The symmetric profile SNLA 0018/50 is a variation on the traditional NACA 0018 created by Sandia National Laboratories specifically for vertical axis wind turbine applications [27] and was adopted for different rotor configurations. The data considered here are provided by Gregorek et al. [20] and are limited to high Reynolds numbers (above 10^6) and angles of attack lower than 30°. As before, the coefficients from Sheldahl are used to extend the database: in this case, the NACA 0018 coefficients are considered. The aerodynamic coefficients for average Reynolds numbers of 1.41×10^6 and 2.52×10^6 are presented in Figs. 9 and 10 respectively.

The databases reported above represent the most popular ones available in the literature and suitable for vertical axis wind turbine simulations. The databases cover the main rotor configurations whose experimental tests have been published and therefore enable their validation for BE-M simulations.

4. Simulation results

The different databases presented in Section 3 are adopted in the simulation model presented in Section 2 in order to compare the simulation results with experimental data. Different rotor configurations characterized by different sizes, working conditions and aerodynamic profiles are considered, in order to establish the database reliability.

Sandia 2 m: Sandia National Laboratories tested a 2 m Darrieus vertical axis wind turbine in both wind tunnel and open-field [1]. A good agreement is found between the two experimental results and, in the present work, the open field measurements are considered. The main rotor data are reported in Table 1.

Table 1
Main geometrical details for Sandia 2 m rotor [1].

H (m)	R (m)	Profile	c (m)	N (–)
2.00	0.98	NACA 0012	58.77	3

The turbine is characterized by a NACA 0012 profile and therefore the databases from Sheldahl, Paraschivoiu, Lazauskas and Jacobs are considered. Two fixed rotational speeds are considered in the tests: 400 rpm and 460 rpm. Given the small turbine size, low Reynolds numbers are experienced by the blade during the revolution, as shown in Fig. 11(a). The blade angles of attack are shown in Fig. 11(b).

The results for the turbine simulation with the different databases are shown in Fig. 12.

The database which best reproduces the experimental results is the Jacobs extended database. The experimental curve is indeed reproduced accurately for both pre- and post-stall operative conditions and both rotational speeds.

Sheldahl and Lazauskas databases provide the same results because the differences in coefficients are only related to angles of attack higher than 15° which, in this configurations, are not very relevant. The results are quite accurate for high tip speed ratios, when the angle of attack is limited. For lower tip speed ratios, when the wind speed is increased, the angle of attack is also increased and, as can be seen from Fig. 11(b), exceeds 10° even in the middle plane, the most productive section. The steep decrease of the lift coefficient for these operative conditions leads to an underprediction with respect to the real blade lift and therefore a penalized estimation in rotor torque.

The database from Paraschivoiu provides the worse estimation. The presence of negative lift coefficients for some angles of attack additionally penalizes the global rotor performances with respect to the Sheldahl simulation, giving an additional shift downwards for the power coefficient curve.

The results highlight that, for small wind turbines experiencing low Reynolds numbers, the Jacobs database should be preferred for BE-M simulations.

Sandia 5 m: Another small wind turbine has been tested by Sandia National Laboratories in their test field [2]. The tests were conducted on two prototypes, both with a diameter of 5 m but equipped with 2 and later 3 blades, all with the same geometry. The main rotor characteristics are reported in Table 2.

The blade is characterized by a NACA 0015 profiles and therefore the same databases as the case before are adopted: Sheldahl, Paraschivoiu, Lazauskas and Jacobs. Results from five rotational

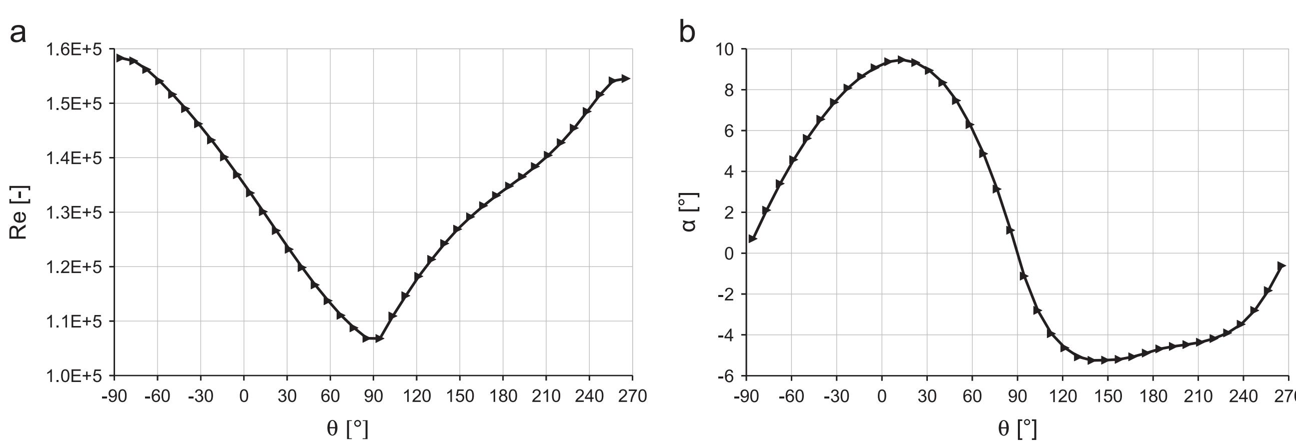

Fig. 11. (a) Reynolds numbers and (b) angles of attack for the middle section of Sandia 2 m rotor with respect to the azimuthal position during a blade revolution for an operative condition of $\lambda = 5$, corresponding to the experimental maximum power coefficient condition.

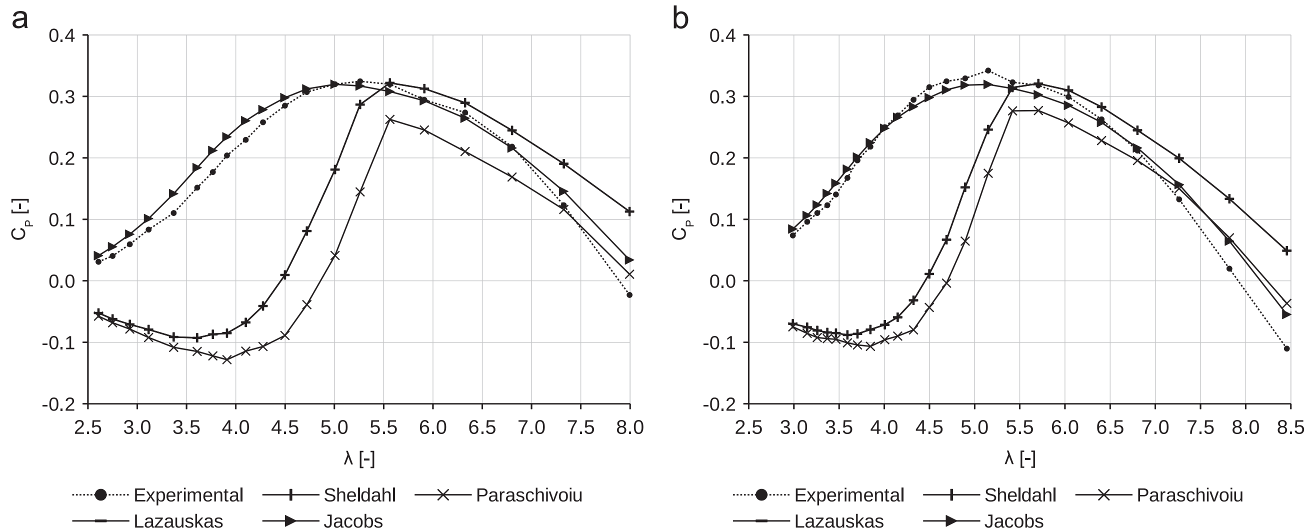

Fig. 12. Power coefficient with respect to the tip speed ratio for the Sandia 2 m turbine, experimental results compared against simulation results with different aerodynamic databases for two rotational speeds. (a) 400 rpm. (b) 460 rpm.

Table 2
Main geometrical details for Sandia 5 m rotor [2].

H (m)	*R* (m)	Profile	*c* (m)	*N* (–)
5.1	2.5	NACA 0015	152.4	2/3

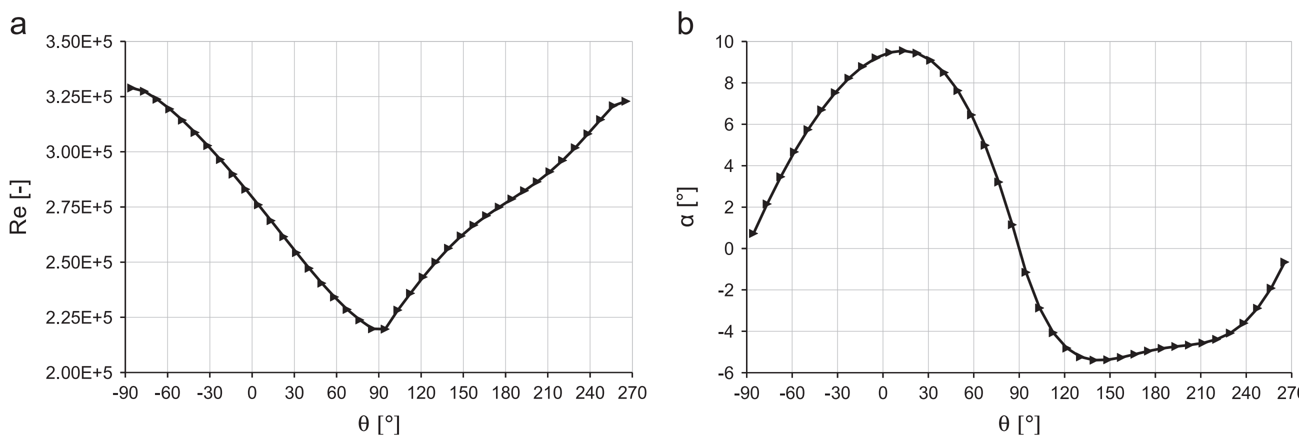

Fig. 13. (a) Reynolds numbers and (b) angles of attack for the middle section of Sandia 5 m rotor with respect to the azimuthal position during a blade revolution for an operative condition of $\lambda = 5$, corresponding to the experimental maximum power coefficient condition.

speeds are reported in the paper: from 125 rpm to 175 rpm. The Reynolds numbers are higher than in the previous case but still lower than those commonly considered in aeronautic applications, as shown in Fig. 13a. The blade angles of attack are shown in Fig. 13b.

The results for the turbine simulation with the different databases are shown in Fig. 14.

The reliability for the rotor simulations appears to be different with respect to the different rotational speeds.

Considering 125 rpm, it is possible to observe that all the databases over-estimate the turbine production for high tip speed ratios. Increasing the wind speed, the Jacobs database still provides the best result being superimposed to the experimental curve, whereas Sheldahl, Paraschivoiu and Lazauskas databases provide an under-estimate prediction linked to the steep decrease in the lift coefficient after the stall occurs. The three databases show mainly the same results since the Reynolds numbers involved are higher than in the previous case and therefore the low Reynolds numbers included in the Paraschivoiu database are not anymore considered.

The experimental data for a rotational speed of 137.5 rpm highlight a strange behaviour for tip speed ratios between 3.0 and 5.5, since the curve experiences a steep change in trend which is not followed by the numerical simulations. All the databases provide reliable results for high tip speed ratios whereas for low tip speed ratio the best results are still achieved with Jacobs database.

Sheldahl, Paraschivoiu and Lazauskas databases show a good approximation for the power coefficient peak for a rotational speed of 150 rpm, whereas Jacobs database provides a slightly underestimated prediction. Again the post-stall behaviour is correctly predicted by this last database whereas the first ones

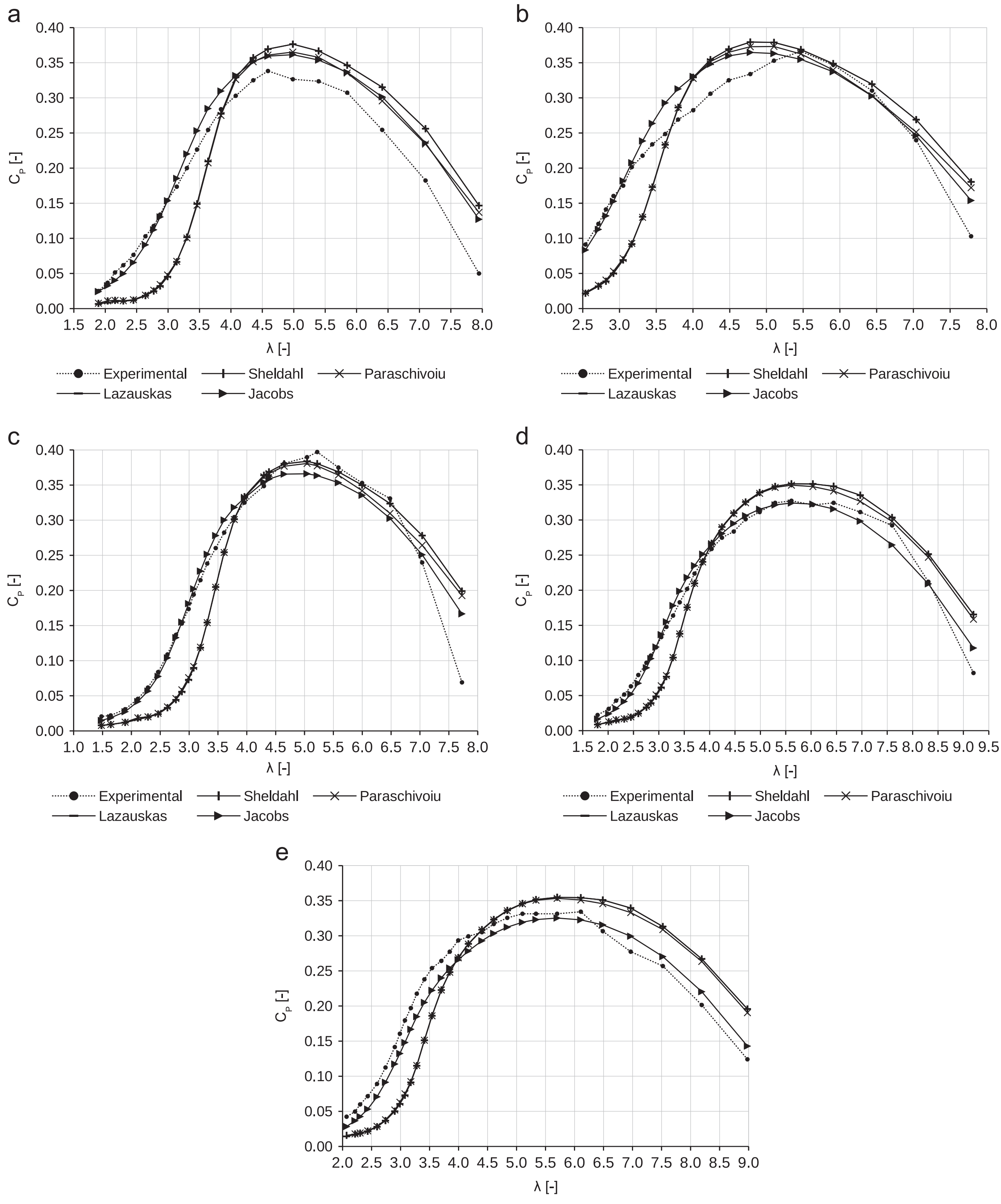

Fig. 14. Power coefficient with respect to the tip speed ratio for the Sandia 5 m turbine, experimental results compared against simulation results with different aerodynamic databases for five rotational speeds. (a) 125 rpm, (b) 137.5 rpm, (c) 150 rpm, (d) 162.5 rpm, and (e) 175 rpm.

under-predict it because of the under-estimation of the lift coefficient.

Finally for the higher rotational speeds and the lower solidity configurations (in this case, only two blades were installed), Jacobs database provides the most reliable result over all the power coefficient curve, exactly predicting both the peak coefficient and the pre- and post-stall behaviour. The same errors for the other databases as in the previous cases are registered.

Concluding, for a rotor configuration characterized by these Reynolds numbers and size, the Jacobs database is suggested to be adopted in order to obtain the most reliable computation.

Sandia 17 m: The 17 m rotor tested by Sandia National Laboratories is the most famous reference case due to the large availability of measurements for various rotational speeds. The turbine has been tested with both 2-blade and 3-blade configurations [3,4]. In the present study, the results from the three blade rotor are considered. The main rotor characteristics are reported in Table 3.

The rotor is again characterized by a NACA 0012 profile as for the 2 m rotor, and the solidities are almost the same. The same databases as before are therefore adopted: Sheldahl, Paraschivoiu, Lazauskas and Jacobs. On the other hand, the Reynolds numbers are considerably increased, as shown in Fig. 15a and therefore a new comparison is worth. Higher Reynolds number databases are in fact less sensitive to small variations in the Reynolds numbers than lower Reynolds number databases and the experimental tests for their estimation less complex. Moreover, Sandia experimentally tested NACA 0012 profile for higher Reynolds numbers and therefore the aerodynamic coefficients are not only numerically derived as for the lower Reynolds number values. The variation in the angles of attack along the azimuthal position for the rotor middle plane is reported in Fig. 15b.

The results for the turbine simulation with the different databases are shown in Fig. 16. The power curves are presented in this case because the authors found them more convenient to compare the discrepancies between the simulation results and the experimental data.

The simulation results for this rotor architecture are in general less accurate than for the previous cases. This could be related to the main difference between this configuration and the previous ones: the presence of two tilted supporting spokes for each blade. Their presence deeply influence the aerodynamic behaviour of the rotor and, since they are profiled as NACA 0012 and tilted, they actively introduce a tangential coefficient C_T which provides additional contributions to both rotor torque and drag, for different operative conditions. Since the basic formulation adopted in the present work does not include any model for the spokes, in order to keep the model simple and not to introduce additional uncertainty factors that would influence the comparison between the databases, their presence is not accounted.

Table 3
Main geometrical details for Sandia 17 m rotor [3,4].

H (m)	*R* (m)	Profile	*c* (m)	*N* (–)
17.01	8.36	NACA 0012	533.4	3

On the other hand the general trend for the power curve is still correctly predicted. The error in the power production is very reduced up to the rotor nominal wind speed for all the rotational speeds. It is possible to observe that Sheldahl, Paraschvioiu and Lazauskas databases provide mainly the same result for wind speed lower than 14 m/s. A small difference is observed for higher wind speeds among Sheldahl/Paraschivoiu and Lazauskas databases because of the glare effect at high angles of attack that is supposed to be corrected only in the second database. The steep decrease after profile stall in all three databases deeply affects the stall characteristics of the turbine, leading to a considerable decrease in the power production. The power decrease is also present adopting the Jacobs database, but with a less steep characteristic. The experimental data highlight a different behaviour for the stalled conditions which can be related to the presence of the spokes and additionally to the dynamic stall, another factor which is not considered in this code and might contribute to a more reliable estimation in these conditions [15].

Overall, the Jacobs database still provides a better result than the other databases in the first part of the power curve and to predict the peak (nominal) power production. The stall production is not correctly predicted because of the limitations in the simulation code more than database reliability.

Sandia 42 m: Sandia National Laboratories published the results for a last turbine with a greater size, 42 m in height and 34 m in diameter [28]. This turbine is characterized by a blade which is designed considering both aerodynamics and structural constraints, being tapered with three different profiles. The chord and the thickness indeed decrease from the shaft connection to the rotor middle plane in order to lower the centrifugal forces and increase the aerodynamic tangential coefficient. Moreover, the blade shape is not a traditional SCS (Straight–Curve–Straight, a convenient approximation for the Troposkien shape [29]), but with a smaller diameter. The main geometrical details are reported in Table 4.

Due to the presence of different airfoils, in this case different databases need to be used. The central part of the rotor is profiled as SNLA 0018-50, a profile which is realized by Sandia National Laboratories derived from NACA 0018 especially for vertical axis wind turbine applications [27]. The database adopted here is only the one provided by Gregorek [20] extended to high angles of attack, since unfortunately no other databases are available for these profiles. The Gregorek database is provided for Reynolds numbers between 10^6 and 4.0×10^6 and it is therefore suitable for the simulated operative conditions as shown in Fig. 17(a).

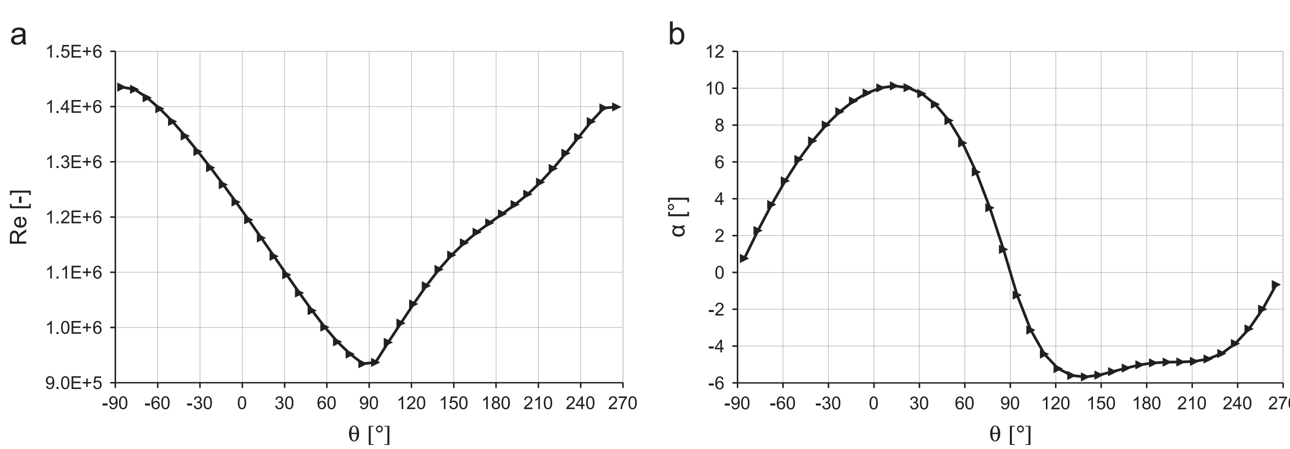

Fig. 15. (a) Reynolds numbers and (b) angles of attack for the middle section of Sandia 17 m rotor with respect to the azimuthal position during a blade revolution for an operative condition of $\lambda = 4.5$, corresponding to the experimental maximum power coefficient condition.

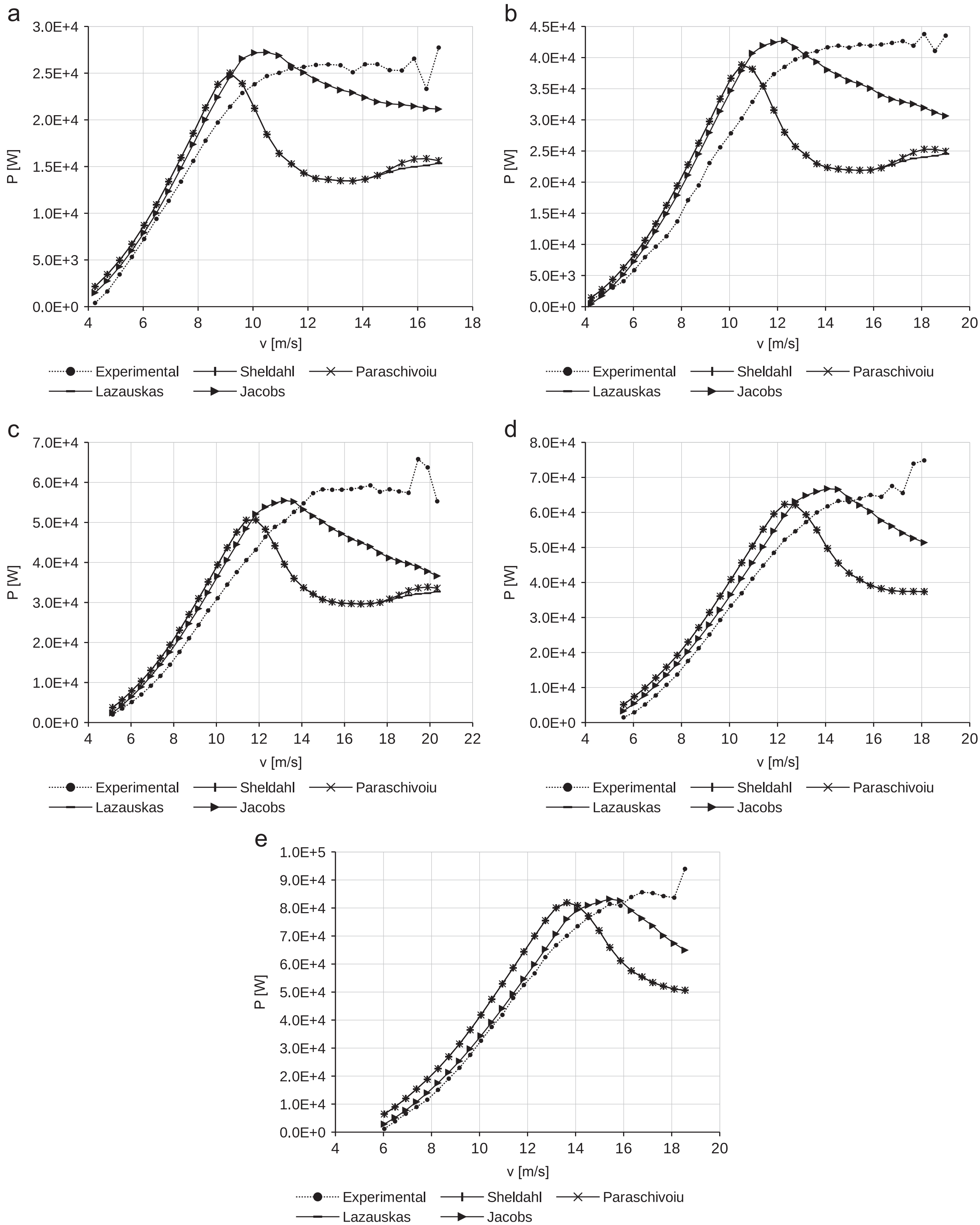

Fig. 16. Power coefficient with respect to the tip speed ratio for the Sandia 17 m turbine, experimental results compared against simulation results with different aerodynamic databases for five rotational speeds. (a) 37 rpm, (b) 42 rpm, (c) 45.5 rpm, (d) 48.4 rpm, and (e) 52.5 rpm.

The NACA 0021 coefficients are instead included in the Sheldahl, Lazauskas and Jacobs databases and are therefore separately adopted and compared. This profile is only adopted in the blade tips and therefore at a small radius from the shaft: the difference in performance estimation due to the databases is therefore expected to be limited. The variation in the angles of attack along the azimuthal position for the rotor middle plane is reported in Fig. 17(b).

The results obtained using different databases for NACA 0021 airfoil and the Gregorek database for the SNLA 0018-50 airfoil are reported in Fig. 18.

The simulation algorithm produces a good estimation for the rotor performance for the rotational speeds of 28 rpm and 34 rpm, whereas for 38 rpm at tip speed ratios lower than 5, the experimental curve experiences a steep decrease which is not followed by the simulated curves. The global agreement of the simulation results confirms that the Gregorek database can be successfully adopted to simulate the SNLA 0018-50 profile in the vertical axis wind turbines. As expected, the differences in the adopted databases for NACA 0021 do not substantially influence the power coefficient curve since this profile is adopted only in a limited region and for structural reasons. Anyway, Jacobs database still provides an estimation closer to the experimental values and therefore should be preferred against Sheldahl and Lazauskas databases. A slight overestimation is present for low tip speed ratios, where the rotor experiences stall conditions: this slight overestimation can be probably corrected by introducing a dynamic stall model.

Magdalen Island 37 m: In 1977 a 230 kW vertical axis wind turbine designed and built by DAF Indal Ltd. was installed in Magdalen Islands, Canada [5,6]. The turbine was characterized by a height of 37 m and a diameter of 24 m. The turbine suffered from an overspeed accident and was eventually equipped with an aerodynamic brake. The turbine blade is profiled as a NACA 0018, a profile which was not adopted in the turbines developed by Sandia. The validation is conducted in order to establish the reliability of the databases for this profile. The main geometrical details are reported in Table 5.

Given the rotor size, the Reynolds numbers expected for this configuration are rather higher with respect to the smaller configurations, as shown in Fig. 19(a). The databases adopted here are again Sheldahl, Paraschivoiu, Lazauskas and Jacobs, even if for the first three databases the expected difference in the results is small because of the high Reynolds numbers involved. The Jacobs database presents also small differences compared to the other ones, mainly located in the post-stall angles of attack, which should not influence extensively the computation since the angles of attack for most of the sectors are lower than 10°, as can be seen in Fig. 19(b) for the rotor middle plane.

The results obtained using different databases for NACA 0018 airfoil are reported in Fig. 20. Even in this case the comparison is conducted on the power curve since the experimental data for one rotational speed appears to be scattered, probably obtained with a few number of measurements for each rotational speed, leading to a power coefficient curve which is not suitable for comparisons.

The simulations provide results which are very close for wind speed up to the maximum production levels. The prediction in this phase is quite accurate for the higher rotational speed whereas for the lower one a discrepancy is registered: the experimental production is lower than the simulated one. On the contrary, for higher wind speeds at 29.4 rpm the experimental production is higher than the predicted: these discrepancies can be related to the dynamic stall phenomena. Instead, the peak prediction is quite accurate with the Jacobs database whereas the other databases provide an underestimated production. This is mainly related to the difference in the lift coefficient among the databases, as can be observed in Fig. 7. Jacobs estimation is higher and the result turns to be more reliable. For higher rotational speeds, the curve is limited to pre-stall conditions because on the test site only in few occasion the wind speed was higher than 15 m/s. The predictions are reliable generally with all the databases, even though it is still possible to observe an underestimation using the Sheldahl/Paraschivoiu/Lazauskas coefficients.

All the databases generally provide a good estimation for the turbine performances but Jacobs database should still be the preferred choice to simulate turbines operating at high Reynolds numbers and adopting NACA 0018 airfoils because of the correct peak prediction.

5. Conclusions

This work presents a review on the different aerodynamic databases available in the literature which can be used for vertical axis turbine simulations combined with Blade Element-Momentum algorithms. The databases should include airfoil coefficients at low Reynolds numbers and for angles of attack from $-180°$ to $+180°$. Some databases included in the comparison were already provided with these characteristics, others are extended by the authors conducting some assumptions, in order to extend the comparison pool.

The simple BE-M simulation without any correction model provided already a good result with most of the databases, although limitations linked to the dynamic stall operative conditions and

Table 4
Main geometrical details for Sandia 42 m rotor [28].

H (m)	*R* (m)	Profile	*c* (m)	*N* (–)
41.9	17.1	SNLA 0018-50/NACA 0021	1.22/1.07/0.91	2

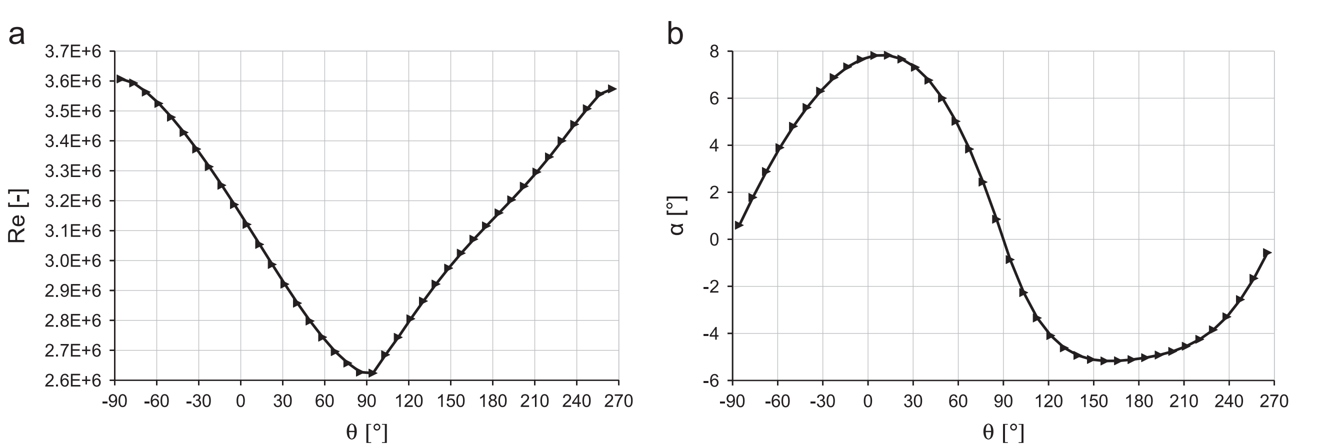

Fig. 17. (a) Reynolds number and (b) angles of attack for the middle section of Sandia 42 m rotor with respect to the azimuthal position during a blade revolution for an operative condition of $\lambda = 6.2$, corresponding to the experimental maximum power coefficient condition.

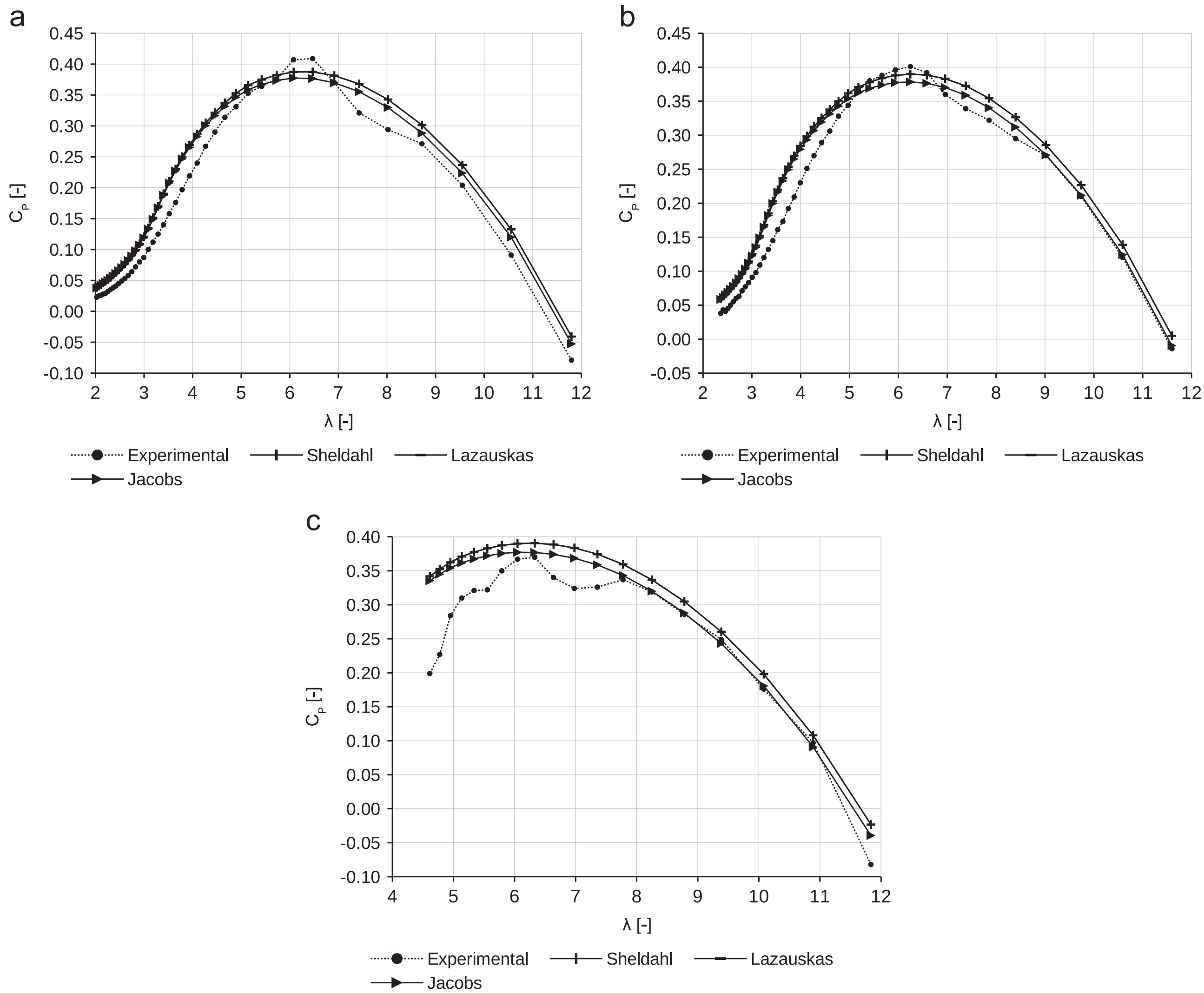

Fig. 18. Power coefficient with respect to the tip speed ratio for the Sandia 42 m turbine, experimental results compared against simulation results with different aerodynamic databases for three rotational speeds. (a) 28 rpm, (b) 34 rpm, and (c) 38 rpm.

Table 5
Main geometrical details for Magdalen Island 37 m rotor [6].

H (m)	*R* (m)	Profile	*c* (m)	*N* (–)
37	12	SNLA NACA 0018	0.61	2

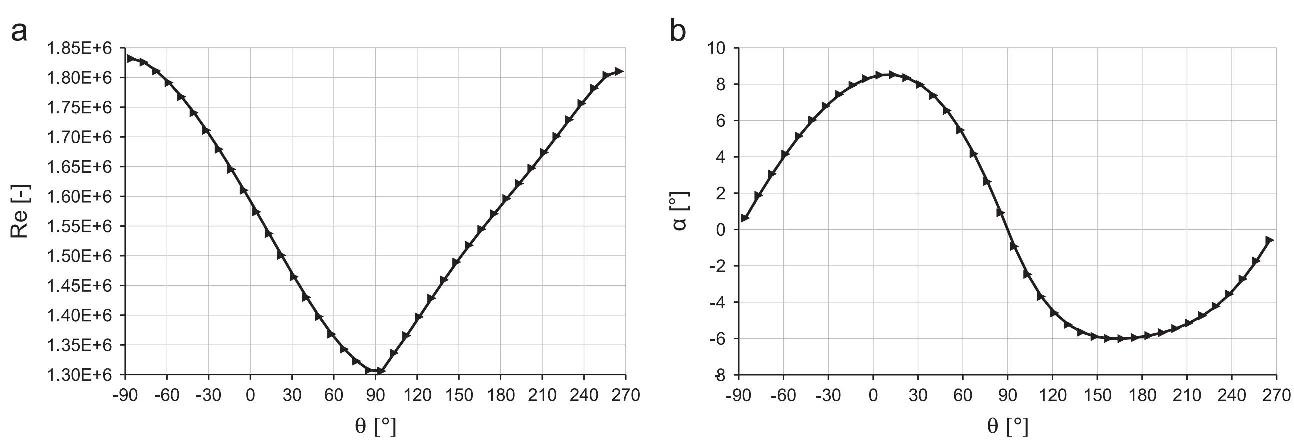

Fig. 19. (a) Reynolds numbers and (b) angles of attack for the middle section of Magdalen Islands 37 m rotor with respect to the azimuthal position during a blade revolution for an operative condition of $\lambda = 6$, corresponding to the experimental maximum power coefficient condition.

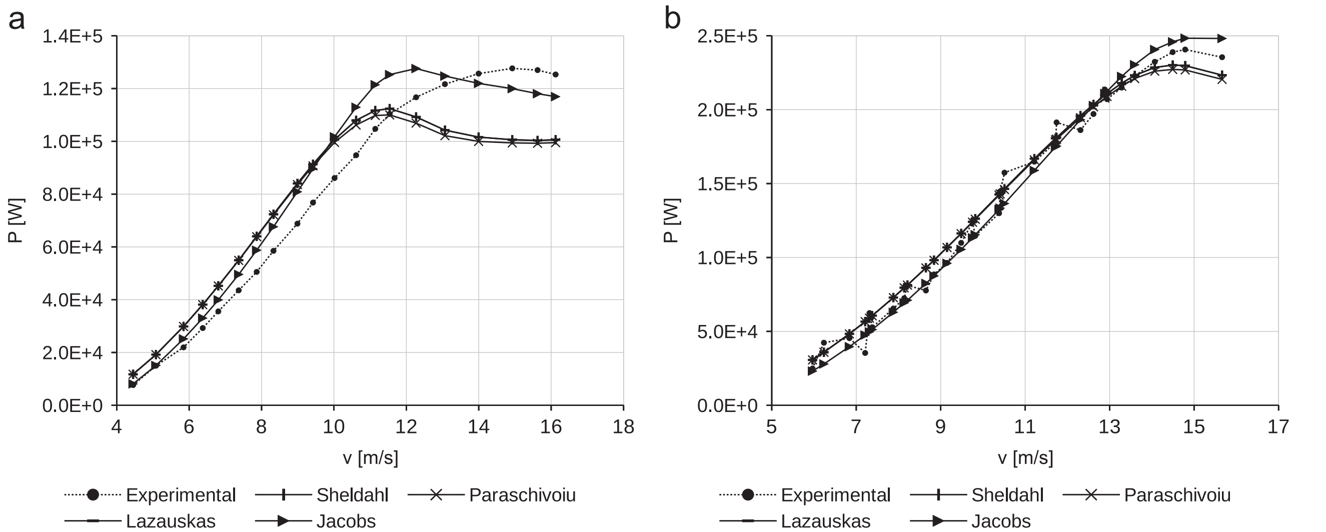

Fig. 20. Power coefficient with respect to the tip speed ratio for the Magdalen Islands 37 m turbine, experimental results compared against simulation results with different aerodynamic databases for two rotational speeds. (a) 29.4 rpm and (b) 36.6 rpm.

spoke presence are highlighted. Recommendation on the database choice can be however drawn in order to select the most reliable one with respect to the applicative case. Especially for rotors operating at low Reynolds numbers, the widely diffuse Sheldahl database and the derived databases from Paraschivoiu and Lazauskas largely affect the computation result leading to under-predicted performances due to the under-estimation of the lift coefficient in post-stall conditions. This result is clearly depicted in the Sandia 2 m and 5 m simulations, where the computation is completely unreliable for low tip speed ratios since the performance drop to unrealistic values. On the other hand, for higher Reynolds numbers this effect is still present but with a more limited influence.

Overall, the authors recommend the adoption of the extended Jacobs database for all the vertical axis turbine computations, since the estimation reliability was always higher or equal with respect to the other databases. Although the database was extended using the aerodynamic coefficient from Sheldahl for high angles of attack, its inaccuracy is limited to a small amount of sectors of the blade and does not affect the overall computational results.

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