Numerical simulation and experimental study of blade pitch effect on Darrieus straight-bladed wind turbine with high solidity

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Abstract

Increasing the solidity in vertical axis wind turbines (VAWT) leads to the decreased coefficient of performance (COP) despite the improved start-up performance. To overcome this problem, the pitch regulation system is proposed in this paper for increasing the solidity. In most of the previous investigations, the effect of pitch angle was tested on low-solidity VAWT at uniform flow conditions and low turbulence intensity in wind tunnel test sections, which are different from the real conditions. In this investigation, the influence of pitch angle on the aerodynamic performance of a small Darrieus-type straight-bladed high-solidity VAWT equipped with a pitch regulation system is investigated numerically and experimentally under realistic condition. The proposed numerical procedure is validated through experimental test results. The COP is measured and calculated at different tip speed ratios and two pitch angles of 0 and 5°. The results reveal 25% enhancement in maximum COP with the increase of pitch angle up to 5°. Moreover, according to the numerical results, higher accuracy can be obtained at lower tip speed ratios for both pitch angles. Then, the numerical method is employed to calculate the power (performance) and torque coefficients as a function of Azimuth position as well as the flow field in rotor affected zone and lateral distance. It is found that increasing the pitch angle at a constant tip speed ratio is followed by accelerated vorticity generation, occurrence of maximum COP at lower tip speed ratio and smoother velocity profile in lateral distances of the rotor.

Keywords Darrieus VAWT · Experimental aerodynamics · Computational fluid dynamics · Pitch angle · Performance coefficient

List of symbols

A_s	Rotor swept area
AOA	Angle of attack
C	Blades chord
C_L	Lift coefficient
C_P	Power coefficient
C_T	Torque coefficient
D	Rotor diameter
H	Rotor height
N	Number of blades
P	Power
R	Rotor radius
T	Torque

TSR	Tip speed ratio
V	Velocity
P	Air density
σ	Solidity ratio
ω	Rotational speed
Ω	Dimensionless vorticity

1 Introduction

Interest in renewable energy technologies has experienced an increasing trend in recent decades regarding the growing chemical and thermal pollutions, rising

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energy demand all over the world, and depletion of fossil fuel resources. Among the renewable sources of energy, wind is proved to be the most economical energy resource with the fastest developing rate. Horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) are known as the basic configurations of wind turbines. The prior configuration is highly developed and currently used in large-scale wind farms, while the latter configuration is mainly installed in urban areas and high turbulent conditions [1, 2]. Darrieus turbine is a type of VAWT operating through lift force in different rotor shapes and configurations [3]. Low start-up torque is considered as the probable disadvantage of Darrieus-type VAWTs prompting researchers to study different geometrical parameters of rotors to alleviate this drawback. In this regard, numerous dimensionless parameters have been introduced in order to investigate the effect of different parameters. In recent years, the positive effect of high solidity ratio on the improvement of start-up torque and self-starting of Darrieus VAWTs has been confirmed in several researches. However, diverse effect of high solidity on the coefficient of performance (COP) has been reported [4]. Nevertheless, it should be mentioned that high solidity is a necessary option in low wind speed conditions. Blade pitch angle has been introduced as a parameter for controlling VAWTs COP [5]. Computational fluid dynamics (CFD) simulations along with experimental measurements can be implemented for better understanding of VAWT. In this investigation, a straight-bladed Darrieus-type VAWT with a high solidity ratio has been studied numerically and experimentally under two different pitch angles in order to determine the effect of blade pitch angle on the aerodynamic performance. In several investigations, various aspects of VAWTs have been considered, which are briefly reviewed further.

In a numerical investigation by Arab et al. [6], the performance and self-starting characteristics of VAWTs were evaluated with the consideration of rotor's moment of inertia. The shear stress transport (SST) transient turbulent model was utilized and it was declared that an increase in solidity was followed by decreased COP average. Furthermore, the maximum COP was calculated at lower tip speed ratios (TSR). The CFD technique was applied by Rezaeiha et al. [5] to study the effect of pitch angle of blades on the VAWT aerodynamics performance. The results revealed the possible enhancement of 6.6% in COP for a particular condition of the studied turbine. Also, dynamic pitching was proposed as an effective approach for further enhancement in performance. Rogowski et al. [7] simulated a two-bladed Darrieus-type wind turbine using a 2D CFD method. They reported a good agreement between the numerical and experimental results with the use of different turbulence models such as SST $k-\omega$ and realizable $k-\epsilon$. A new model for performance prediction on the basis

of CFD was proposed by Castelli [2]. Moreover, numerical investigation of a small VAWT as well as experimental implementation of wind tunnel test were conducted by Howell et al. [4]. The results of 3D numerical model presented 20% error compared to wind tunnel data. Li et al. [8] utilized 2.5-D large eddy simulation (LES) to simulate a VAWT under conditions of high angle of attack (AOA) flows. Despite the inability of 2.5-D LES in capturing the effects of tip vortex, this model was confirmed to be an accurate method for evaluating the aerodynamics performance of VAWTs. Horb et al. [9] pointed out the use of variable pitch control for a VAWT and expressed the enhanced maximum COP up to 15%. In a numerical study, Danao et al. [10] assessed the effect of chamber and thickness of blades on the aerodynamics characteristic of VAWT 2-D and stated the positive effect of chamber on VAWTs start-up. More relevant information can be found in the published literature [11–17]. Regarding the recent investigations, Posa [18], applied LES simulation to investigate influence of tip speed ratio on VAWT lateral wake and compared numerical results with particle image velocimetry (PIV) results of wind tunnel test. His results revealed that an increment in TSR would lead to momentum deficit in the wake. Moreover, the effect of blade folding motion on VAWT performance was explored by Guo et al. [19] and the diminished maximum performance by folding was declared.

However, in this paper, it is aimed to determine the effect of blades pitch angle on a specific small straight-bladed Darrieus-type VAWT with high solidity under various TSRs from numerical and experimental viewpoints. For this purpose, an experimental set-up was assembled in Isfahan Science and Technology Town, which provides desirable wind conditions and measurement instruments. Furthermore, a 2D numerical approach was implemented for VAWT and the obtained results were compared with experimental results for the sake of validating the numerical procedure for future studies. $k-\omega$ SST turbulent model was implemented in fully transient modeling and simulation based on dynamic mesh and six-DOF methods. The output power was measured from experimental set-up and compared with numerical results in order to define the accuracy of the numerical method. The rest of this paper is organized as follows: in Sect. 2, the geometry of the studied model along with the detailed characteristics of the blade airfoil are presented. Experimental setup, measurement techniques and embedded sensors are also explained in Sect. 3. Section 4 is dedicated to the numerical methodology, domain and boundary conditions, grid information and turbulence modelling. Moreover, experimental and CFD results are provided and compared in Sect. 5 and Finally, Sect. 6 is devoted to the main conclusions of this investigation.

Fig. 1 NACA630018 dimensionless geometry (x and y values to chord length c)

Table 1 Geometrical features of the tested model

Parameter	Value
D_{rotor} (m)	0.5
H_{rotor} (m)	0.5
N (–)	3
Blade profile	NACA630018
$C_{\text{blade profile}}$ (cm)	10
σ (–)	1.2
Material	Wood

2 Model geometry

In this investigation, symmetric airfoils were used in VAWTs for controlling the (Lift to Drag) L/D ratio in downstream blades and achieving higher COP in comparison with chambered airfoils. Conventionally, NACA 4-digit symmetric airfoils have been extensively used in Darrieus-type straight-bladed VAWTs (for example, several numerical and experimental studies as well as commercial applications are conducted with the use of NACA0015–NACA0022 [3]). However, in this study, NACA 6-series, which is considered as popular airfoil series in HAWTs, is selected regarding the low drag coefficient as a result of top line shape. Accordingly, NACA630018 was employed to control the laminar boundary condition and generate high L/D ratio. Furthermore, as the two last digits represent the maximum thickness, the maximum thickness of NACA630018 is equal to NACA0018, which has been broadly employed in VAWTs. Figure 1 represents NACA630018 geometry in dimensionless coordinates.

Solidity is considered as another influential geometrical parameter and its optimum value for maximum COP has been reported within the range 0.3–0.5 [20]. In this case, solidity was set 1.2. Furthermore, other geometrical features of the studied turbine are summarized in Table 1.

3 Experimental set-up

Despite the widespread usage of wind tunnel experimental test for characterizing the aerodynamics performance of VAWTs, some inaccuracies associated with the solid and wake blockages may restrict its application. It is worth noting that the effect of tunnel walls is not negligible at high blockage ratios [4], meanwhile, the turbulence intensity of air stream through the test section is far smaller compared to the real conditions.

In this regard, an experimental setup was fabricated in Isfahan Science and Technology Town to establish desirable wind conditions for the measurement of various parameters. Two variable speed DC motors were connected with (Remote Controlled) RC speed controls to induce wind speed using two 3-bladed impellers. The impellers were installed symmetrically with respect to the turbine's plane of symmetry. Furthermore, TESTO 400 unit was employed to measure the wind speed and rotational speed of turbine shaft. A remotely-controlled servo-motor and a mechanical mechanism were attached to the turbines rotor for applying an accurate blade pitch angle. Additionally, the shaft of the turbine was coupled to a low rpm DC generator; thus, the output current and voltage were measured using an ammeter. Figure 2 illustrates the fabricated experimental setup in this investigation. It should be noted that for producing a lower rotor moment of inertia, blades and connecting arms were manufactured from Balsa wood through laser cut method as depicted in Fig. 3.

4 Numerical setup

The dimensions and the boundary conditions of the whole studied domain are depicted in Fig. 4. According to reference [2], for the computational domain with the width of approximately 80 times of the rotor diameter in the non-slip sidewalls boundary conditions, the domain solid blockage would be less than 0.32%. The represented boundary conditions in Fig. 4 are also provided in Table 2. Since no air flow was presented in the channel, the domain width was considered to be 20 times of the rotor diameter. Similar to Li et al. [8], the outlet condition after turbine was considered to be 12 times of the rotor diameter to ensure fully developed wake flows. An initial geometry was tested with the downstream size equal to 12 times of rotor diameter. The observed backflows on the boundaries indicate that the wake flow would not be fully developed for the considered case and boundary conditions. In this regard, the domain width

Fig. 2 Experimental setup schematic

Fig. 3 Manufactured blade and tested turbine

Fig. 4 Computational domain schematic and dimensions

Table 2 Boundary conditions

Number	Physics	Condition
1	Incident wind condition	Velocity inlet
2	Domains boundary far away from rotor	Symmetry
3	Domains boundary far away from rotor	Symmetry
4	Rotor blades	Wall
5	Sliding intersection	Interface
6	Outgoing boundary	Pressure outlet

equal to 10 and 40 times of the rotor diameter were set for the upstream and downstream after the turbine, respectively.

Despite the non-uniform upstream wind speed on turbine blades regarding the boundary layer profile in the vicinity of table surface, uniform incident wind speed was applied in 2-D numerical simulation. According to the $\frac{\delta}{x} = 0.385R_e^{-0.2}$ relation, the boundary layer thickness was 5.65 cm. Additionally, the distance between the table and bottom surface of rotor was 3.2 cm. As in [21], at $\frac{\delta}{y} \geq 0.6$, velocity profile was approximately smooth. In this case,

only 4.9% of blade length was affected by this smooth area of boundary layer which is negligible.

The numerical domain was divided into two areas; a rotational sub-grid zone simulating the rotation of turbine by moving mesh and the main outer domain. It was assumed that the blades of turbine and rotational sub-grid were rotated with an equal angular velocity. The turbine's blade profile in the rotational sub-grid was enclosed with an elliptical area, which would lead to the precise flow field solution with the use of structured quadratic mesh and progressive rate of wall boundaries. Additionally, an unstructured triangular mesh was generated for the rest of the rotating sub-grid zone. Near-wall cell sizes were selected so that to achieve less than unity y^+ on the blade profiles; thus, laminar sub-layer on the boundary layer of airfoils would be resolvable. At $TSR = 2.5$, maximum, minimum and mean values of y^+ were calculated as 0.9673, 0.6284, 0.8426, respectively. Moreover, mesh independency for the considered CFD model was also studied and the results are provided in Fig. 5. As can be seen, finally, a grid with 124,095 cells was selected. Torque coefficient was calculated for various azimuth angles of rotor in the first revolution after the initial steady-state solution. It should be noted that only the cells in the vicinity of blades in rotational zone were varied.

A structured quadratic mesh with refinement near the rotational zone was applied to the domain. Also, the wake behind the turbine rotor was meshed with finer cells to enable the complete interaction of vortex cores and achieving the subsequent enhancement in calculation accuracy of wake flow. The interface between the rotating

zone and the main outer domain was a non-conformal interface with the coupled grids to allow the turbine rotation. Generated meshes in different zones are detailed in Fig. 6.

Regarding the lower Mach number of induced velocities than 0.3, incompressible momentum equation and continuity equation are the appropriate choices for solving the VAWT flow field [8]. Various turbulence models have been employed by previous researchers, with both RANS and eddy simulations (LES and DES) and validated with different experimental tests [22]. Because of the unsteady nature of wind turbine flow field, 3-D LES revealed the most acceptable results; however, its computational cost was too high for this method. Meanwhile, 4-equation SST turbulence model was used by Rezaeiha et al. [16] and a good agreement with experimental data was declared. In the present study, incompressible 2-D transient RANS equations were solved with the coupled pressure-velocity scheme using the moving (sliding) mesh. Furthermore, 4-equation Transition SST with DES scale-resolving simulation option was employed as a turbulence model. Table 3 illustrates the implemented numerical simulation setup and discretization schemes. Approximately 32 h was required for each revolution of turbine using Intel Core i5 3360 M and 12 GB of RAM, which can be improved by the use of GPU processing unit. The meshes were generated with the help of GAMBIT software, and Commercial CFD software of Ansys Fluent v.16 was employed for solving the numerical governing equations.

The initial solution was obtained based on steady-state RANS and $K-\epsilon$ turbulence model. Then, a specific time step for each TSR was set such that the turbine was rotated 2° per each time step and the convergence criteria were set to 10^{-4} for all absolute residuals. Data were extracted after five complete rotations of the turbine and convergence in the torque-time diagram was observed.

5 Results and discussion

Several procedures have been proposed for the initial design and evaluation of VAWTs. Since all of them require the aerodynamics characteristic of blade profiles [16, 17, 20–25], an initial simulation was completed with NACA630018 airfoil through the use of viscous panel method and CFD technique to estimate the lift and drag coefficients at various AOAs. XFOIL open-source code was used for implementing the viscous panel method and the corresponding results were compared with the results of 2-D CFD steady-state simulation as depicted in Fig. 7.

According to this figure, a good agreement between the mentioned procedures can be observed at low angles of attack; however, with the initiation of boundary layer

Fig. 5 Mesh independency study. Torque Coefficient C_T versus Azimuth position of the VAWTs rotor

Fig. 6 Detailed generated mesh for numerical domain

Table 3 Numerical setup and discretization methods

Subject	Method
Solver	Pressure based
Time	Transient
Turbulence model	Transition SST_DES with curvature correction
Pressure–velocity coupling	Coupled
Gradient discretization	Least square cell based
Pressure discretization	Second order
Momentum discretization	Bounded central differencing
Turbulent K and ϵ	Second order upwind
Transient formulation	First order implicit

separation, more accurate aerodynamics load coefficients were obtained through CFD at higher angles of attacks. An increased L/D ratio can be seen in AOAs less than 7° , which was followed by a decreasing trend, so that the maximum L/D ratio was occurred near 7° AOA for NACA630018.

The average COP trend achieved from the CFD simulations and experimental tests for various tip speeds are provided in Fig. 8. The COP and TSR can be defined as [2]:

$$C_p = \frac{P_{ave}}{\frac{1}{2} \rho A_s V_{wind}^3} \quad (1)$$

$$TSR = \frac{\omega R_{Rotor}}{V_{wind}} \quad (2)$$

Fig. 7 Aerodynamic characteristics of NACA630018

Fig. 8 Coefficient of performance in various tip speed ratios

Regarding Fig. 8, the maximum COP for the pitch angle of 5° was 25.41671% higher than the maximum COP for the pitch angle of 0° . Additionally, the occurrence of maximum COP at lower TSRs with the increase in the pitch angle can be seen, which can be justified by the decrease in the blade's relative AOA during the transition from lower to higher TSR values. Furthermore, CFD results indicated higher accuracy at lower TSRs. Moreover, positive COP at low tip speeds was attributed to high solidity. Solidity is one of the main dimensionless ratios in the determination of rotational velocity

corresponding to maximum COP. Note that higher solidity leads to lower tip-speed ratios and lower efficiency [4]. Besides, 14, 15.9 and 33.5% deviation in the CFD results from experimental measurements were obtained in pitch = 0 for the respective values of TSR equal to 1.5, 2 and 2.5. In similar manner, for pitch = 5, torque values were calculated to be negative at TSR equal to 1 and 2.5, and 10.79% and 16.07% deviations in CFD results from experimental measurements were seen at the respective TSRs of 1.5 and 2.

Solidity is defined as Eq. (3) [16]:

$$\sigma = \frac{N_{blade} C_{blade}}{R_{rotor}} \quad (3)$$

The pitch angle is an influential parameter on the power generated by the turbine. However, the optimum fixed pitch angle should be calculated so that to achieve the positive maximum value of COP as well as highest start-up torque.

Comparison of the numerical simulations with experimental measurements revealed the capability of the numerical procedure using Transition SST along with DES scaled-resolving turbulence model in predicting the shape and curve of experimental data as well as accuracy in capturing the maximum COP in tip speed ratio. The discrepancies between experimental and numerical results were originated from the inabilities of 2-D simulations. For instance, the neglect of tip losses as well as effects of upper and bottom rotor arms on the moment of inertia and drag force of rotor in 2-D simulations can be mentioned as the sources of error. Also, rotor arms will produce turbulent vortices which effect the aerodynamic performance of downstream blades [17, 20].

The coefficient of torque for TSR = 1, 1.5, 2, 2.5 at zero pitch angle is illustrated in Fig. 9. For constant rotational speed at each TSR, the COP as a function of the Azimuth angle can be also seen in Fig. 9. Based on this figure, the highest averaged C_T was occurred at TSR = 1.5. Furthermore, it can be seen that the positive area of C_T was maximum for TSR = 1.5 and minimum for TSR = 1. The coefficient of torque is defined as Eq. (4) [2]:

$$C_T = \frac{T_{rotor}}{\frac{1}{2} \rho A_s R_{rotor} V_{wind}^2} \quad (4)$$

The areas with negative C_T were developed as the blades were entered in dynamic stall condition, causing a diminished L/D ratio. Dynamic stall was occurred due to high AOA through the blade's revolution and influence of shed wakes of the upwind blades on the downstream blades.

Fig. 9 Evolution of C_T as a function of Azimuth position for $TSR=1$, 1.5, 2, 2.5; respectively in pitch = 0

According to the higher reliability and accuracy of the numerical results at $TSR=1.5$ and 2 for both pitch angles and regarding the discussions in previous paragraph, Fig. 9 presents comparative diagrams of Torque Coefficient (C_T) at $TSR=1.5$ and 2 for pitch angle 0° and 5° respectively. According to Fig. 10 for $TSR=1.5$, the average and positive area of C_T at pitch = 5 was higher than that at pitch = 0, causing a higher COP in Fig. 8. An increase in the pitch angle led to elevated AOA in the

downstream blades condition and augmented L/D ratio in these areas. Also, the diagram of C_T at $TSR=1.5$ for pitch = 5 had a smoother peak in comparison to pitch = 0 which was related to delayed dynamic stall. On the other hand, at $TSR=2$, most of the area for pitch = 5 diagram was negative suggesting lower AOA in the revolution of blades.

Figure 11 illustrates C_T for a single blade as a function of Azimuth position at $TSR=1.5$ for pitch = 0 and 5. According to this figure, the average torque coefficient for a single blade with pitch = 5 was higher than the same blade with pitch = 0 at $TSR=1.5$. In addition, the constant value of TSR represented the equal influence of shed wakes for both pitch conditions and consequently, the influence of AOA on the torque coefficient can be concluded. Note that the blades at $TSR=1.5$ experienced the optimum AOA with pitch angle 5.

The magnitudes of instantaneous vorticity for three Azimuth positions are presented in Fig. 12. Since it is a 2D simulation, and regarding the incompressible vorticity transport equation, the vorticity was generated from the wall and diffused through fluid viscosity in the x-y plane [13–15].

Wider high vorticity distribution zones can be seen for pitch = 5 as depicted in Fig. 12. An increase in the pitch angle was resulted in more interactions between the solid wall and viscous flow and accordingly, wider high vorticity zones were obtained. Note that the shape of the vorticity distribution at both pitch angles was similar, but the distribution of high vorticity region was wider for pitch angle of 5.

Fig. 10 Evolution of C_T as function of Azimuth position for pitch angle 0 (red) and 5 (green) in $TSR=1.5$ and 2 respectively

Fig. 11 Evolution of CT as function of Azimuth position for a single blade at TSR = 1.5; pitch = 0 (red) and pitch = 5 (green)

Better understanding of the flow development in VAWT can be achieved from Figs. 13 and 14, which represent the pressure distribution and dimensionless velocity distribution in the rotating zone at the end of 20 revolutions and TSR = 2, respectively. According to these figures, more variation in pressure and velocity distributions was experienced by the first blade by varying AOA in dynamic stall condition when pitch angle increased up to 5° at azimuth = 0. Since two other blades were located in

downstream condition, quasi-invariant pressure and velocity distributions were achieved for them.

Similarly, the dimensionless vorticity, Ω , was defined as Eq. (5), [26] and the results of this parameter in the VAWT lateral distance at TSR = 2 for pitch angle = 0 and 5 are provided in Fig. 12. Generally, two types of vorticity were generated in x-y plane, which were characterized as clockwise (red) and anticlockwise (blue). Both types were induced by relative velocity between free stream and rotating blades.

$$\Omega = \frac{(Z_vorticity) * C}{V_{wind}} \quad (5)$$

However, according to Fig. 15, shed wake region became longer when pitch angle was increased to 5°. Also, at lower lateral distances, wake region was wider for pitch = 0 but with vorticity interactions and momentum transports in lateral flow, wake region became wider at lateral distances equal to 10 m, for pitch = 5.

Regarding the significant effect of wake characteristics on the aerodynamic design of single-bladed turbines and the optimal placement of wind-farms [11], dimensionless stream velocity in the distances of 1, 2, and 3 times of the rotor diameter were calculated and represented in Fig. 16 at TSR = 2 for both 0 and 5 pitch angles. This parameter was calculated after 20 revolutions of the turbine when the fully developed wake was achieved regarding the Azimuth position. According to Fig. 16, the averaged velocities for pitch = 5 were lower than same parameter for pitch = 0 at 1D and 3D lateral distance. Conversely, the averaged velocity for pitch = 5 was higher than the corresponding parameter for pitch = 0 at 2D lateral distance. The turbine

Fig. 12 Vorticity magnitude (1/s); TSR = 2

Fig. 13 Pressure distribution in the VAWT rotational zone at TSR=2

Fig. 14 Dimensionless Velocity (V/V_{wind}) distribution and stream lines in the VAWT rotational zone at TSR=2

wake was developed during the rotation from the generated shed vortices [16]. The transfer of vortices towards the downstream was resulted in the variation in velocity profile behind the turbine. The changes in the magnitude of vortex was a function of variation in AOA. The wider region of vorticities in pitch = 5 had led to a greater influence on the velocity profile in lateral distances.

6 Conclusion

In this paper, a small straight-bladed VAWT with high solidity ratio was fabricated and tested under realistic conditions. Furthermore, numerical simulations were conducted to evaluate the aerodynamic performance

Fig. 15 Dimensionless Vorticity in lateral the VAWT wake at TSR=2

of the turbine at various tip speed ratios and two pitch angles 0 and 5, in order to examine the influence of the pitch angle on the aerodynamic characteristics of the turbine. The results revealed the enhancement in maximum COP and sharper CP_TSR diagram as a consequence of increase in the pitch angle. The maximum CT was occurred at TSR for turbines without pitch angle, but the maximum CP was occurred at $TSR = 2$. Moreover, it was found that the averaged C_T was increased with elevating the pitch angle at $TSR = 1.5$, which was followed by a decreasing trend at $TSR = 2$. Single blade C_T

was increased with the rise in the pitch angle at $TSR = 1.5$. Likewise, the vorticity generation was increased due to elevation of the pitch angle, causing an increased AOA. Finally, the increase in the pitch angle had led to a significant influence on the velocity profile in the lateral distance of the turbine and generated lower velocity wakes. In summary, the obtained results in this study revealed the pitch regulation as a guaranteed way to use VAWT with higher solidity with the capability to start-up at lower wind speed conditions. So, a closed-loop control system would be an idea for future investigations.

Fig. 16 Cross stream dimensionless velocity profile in 1D, 2D and 3D lateral distance of turbine (CFD results)

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Data availability Parts of the data and materials are available upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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