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Enhancing Efficiency of H-Darrieus Wind Turbines Through Experimental and Numerical Investigations of Double Darrieus Configurations

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ABSTRACT

This research paper presents a comprehensive investigation of the performance and aerodynamic characteristics of a double-blade Darrieus wind turbine utilizing a NACA 0018 airfoil. The study combines wind tunnel testing and numerical simulations using Ansys software to analyze the turbine's behavior under varying wind conditions. Experimental measurements of torque, power output, and blade forces were obtained, while computational fluid dynamics simulations provided insights into flow patterns and pressure distribution. The results demonstrated close agreement between experimental and numerical approaches, validating the accuracy of the computational model. The analysis highlighted the influence of wind speed on turbine performance and the favorable aerodynamic characteristics of the NACA 0018 airfoil. The findings contribute to wind turbine design optimization and offer valuable insights for future research in renewable energy. Furthermore, the research identified the optimum case in the experimental method for the double-blade Darrieus vertical axis wind turbine. The results revealed that the most efficient position is situated at a distance of 4 cm and 3 cm from the rotor, which corresponded to 40% to 30% in terms of the distance ratio. Notably, a 6.7% improvement is observed when comparing single blade and double blade numerical results.

Keywords:
Experimental; CFD; wind energy; VAWT; Darrieus turbine

1. Introduction

The Vertical Axis Wind Turbine (VAWT) is gaining prominence in the realm of small-scale wind power due to its notable benefits, which encompass structural simplicity, wind direction autonomy, absence of a yaw mechanism necessity, resilience to turbulent winds, cost-effectiveness, simplified maintenance, and reduced noise emissions. Numerous studies have delved into enhancing wind turbine designs and performance. Bošnjaković *et al.,* [1] explored minor design modifications, including rotor blade aerodynamics, active rotor blade rotation control, and aerodynamic brakes. Li [2], Kumar *et al.,* [3], and Ghasemian *et al.,* [4] respectively scrutinized the development of Darrieus turbines, while Islam *et al.,* [5] compiled primary aerodynamic models for predicting the performance

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and design of straight-bladed Darrieus-type VAWTs. Bangga *et al.,* [6] extensively evaluated different assessment methods, from DMST to fully resolved CFD approaches.

Wind turbine solidity investigations were carried out by Bangga *et al.,* [6], Singh and Biswas [7], and Soultanzadeh and Moradi [8], revealing the relationship between solidity, power coefficient, and performance. Cambered blade aerodynamics were addressed by Rainbird *et al.,* [9], Chaitep and Chaichana [10], and Matrawy *et al.,* [11]. Notably, Zidane *et al.,* [12] study Enhancing H-Darrieus VAWT performance by using upstream deflectors. Investigated deflector configurations and compared turbine performance with and without wind rotor barriers. Validated CFD models provided novel insights on deflector effects. Provided that the Single deflector increased moment coefficient by 24%, two deflectors increased it by 22% within optimal tip speed ratio range.

Several researchers, including Howell *et al.,* [13], Rahman *et al.,* [14], Rahman *et al.,* [15], Parker and Leftwich [16], and Alaimo *et al.,* [17], concentrated on improving VAWT designs, assessing aerodynamics, and employing CFD simulations for better understanding. The combination of Savonius and Darrieus turbines are explored by Bhuyan and Biswas [18], and Hosseini and Goudarzi [19] numerically designed, simulated and evaluated the performance of an innovative hybrid VAWT to obtain an extended operational range and enhance self-starting capabilities using Ansys. A hybrid VAWT consisting of a two-blade modified Savonius Bach-type rotor and a three-blade Darrieus turbine is numerically modeled and analyzed to calculate the characteristic parameters of the rotor system. Nenaey *et al.,* [20] aimed at numerically combining the favor characteristics of Savonius and Darrieus turbine by producing a hybrid VAWT and evaluated its performance. Hammond *et al.,* [21] aimed at designing a VAWT for urban use. Mohammed *et al.,* [22] intended to design, fabricate and experimentally investigated the performance of hybrid VAWT on residential buildings. Pallotta *et al.,* [23] experimentally described a novel hybrid Savonius-Darrieus combined rotor. They aimed optimizing performances in medium-low wind regimes. Alam and Iqbal [24] presented the design of a hybrid turbine based on a straight bladed Darrieus (lift type) turbine along with a double step Savonius (drag type) turbine.

Still Darrieus turbine has its self-starting problem and as a solution it may be combined in Double-Darrieus hybrid system to be self-starting and to have a high-power coefficient. Ahmad *et al.,* [25] emphasized designing a straight-bladed Double-Darrieus hybrid VAWT. To improve the self-starting characteristics and to enhance the low wind speed performance, Kumar *et al.,* [26] experimentally proposed a Dual rotor Darrieus Turbine (DD) with secondary rotor in addition to the primary rotor (two set of blades). Their results indicated that the novel dual rotor had improved the self-starting capability at the reduced power performance. In addition to the inability to self-start, in a broad sense, research on hybrid Darrieus turbines has highlighted challenges associated with a high tip speed ratio. Investigations have identified issues linked to deflector performance during alterations in airflow direction, which can impact efficiency. In certain instances, these challenges could potentially lead to a decrease in overall turbine efficiency.

The novelty of the presented study is to improve the overall Efficiency of Darrieus wind turbines thought Double rotor configuration. This involves identifying and developing designs that can maximize the Efficiency. The present study has been undertaken with the following objectives:

i. Study single blade, Numerical and Experimental then compare between them.
ii. Study the effect of a Double Blade numerically and experimentally.
iii. Study the effects of different factors such as location of the Second blades and wind speed on the power coefficient.
iv. Compare power coefficient results between single and double blade turbines.

2. Methodology

2.1 Experimental Setup and Instrumentation

The experimental setup consists of turbine base carrying Darrieus shaft, load cells and encoder. This arrangement is at center inside open type wind tunnel that has a test section of 30 x 30 cm with 1 m length. Air velocity is measured using a calibrated Pitot tube. Darrieus turbine has NACA0018 airfoil and 20 cm length, 20 cm diameter, 35 cm chord length and solidity of 1.05. Air speeds in the wind tunnel are comparative to average range of wind speeds in Egypt by employing Reynolds number formula as part of the similarity which is based in Eq. (1) to Eq. (4) [27]. Actual air velocity is calculated to be from 2.3 to 4.4 m/s.

$$Re_{model} = Re_{actual} \tag{1}$$

$$\frac{\rho v d}{\mu}_{model} = \frac{\rho v d}{\mu}_{actual} \tag{2}$$

$$v_m d_m = v_a d_a \tag{3}$$

$$v_a = 0.1 * v_m \tag{4}$$

Power and power coefficient can be calculated from Eq. (5) and Eq. (6) [28]:

$$p = T * \omega \tag{5}$$

$$C_p = \frac{P}{0.5 * \rho * V^3 * A} \tag{6}$$

2.2 Numerical Simulation and CFD Modeling

A domain is adequate to two-dimensionally simulate the performed conditions of wind-tunnel in experimental case, see Figure 1. This allows comparison with both wind-tunnel measurements and numerical simulations. Numerical domain contains three sub-domains; two stationary and one rotating sub-domains. Inner and outer diameters of the rotating domain are 0.17 and 0.23 m, respectively. The lift boundary is configured as a velocity inlet, while the right boundary functions as a pressure outlet. Upper and lower boundaries were set as walls. The airfoil surfaces were modeled as walls with a no-slip condition.

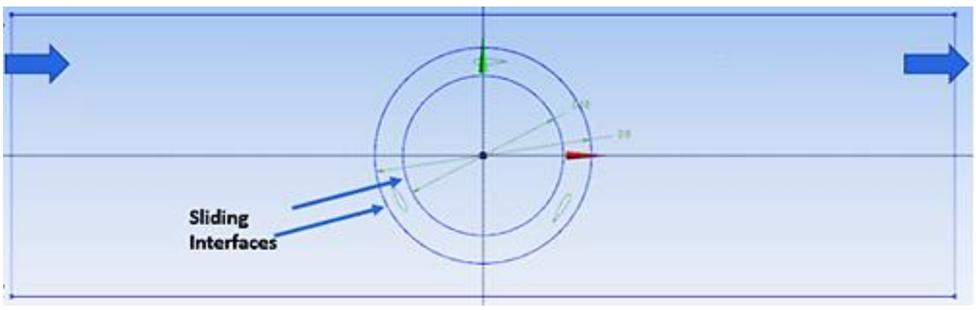


Fig. 1. Darrieus turbine's domain

An unstructured mesh of quadrilateral elements is generated for precise boundary layer resolution around the airfoil (Figure 2). A mesh independency analysis indicated that a mesh with 7.7 × 10^4 elements yielded comparable lift coefficient values to larger element counts. This mesh employed smooth transition inflation, ensuring accuracy and computational efficiency. Mesh specifics, such as transition ratio, layer count, and wall distance, were carefully set to maintain optimal conditions for the wind turbine blade airfoils. Mesh views near turbine blades are illustrated in Figure 3.

CFD model utilized the two-dimensional unsteady Reynolds-averaged Navier-Stokes equations (U-RANS) and incorporated k-ω SST turbulence model to capture the turbulent effects [12], Time step (Δt) is calculated to be Δt = 0.00018 s. The angular velocities are calculated using Eq. (7) according to wind speeds [28].

$$v = \omega r \tag{7}$$

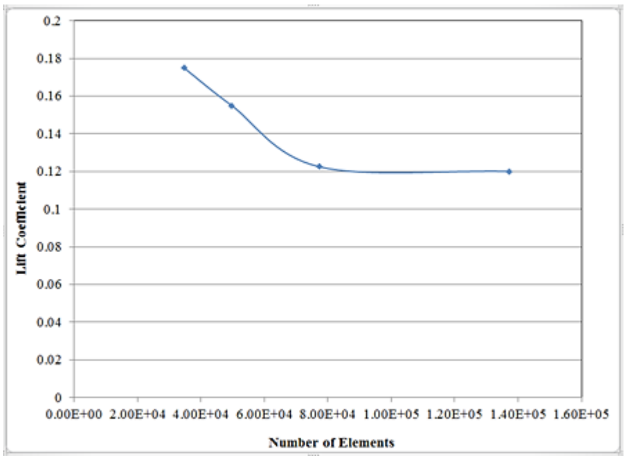


Fig. 2. Relation between Lift coefficient and number of elements at air velocity of 23 m/s.

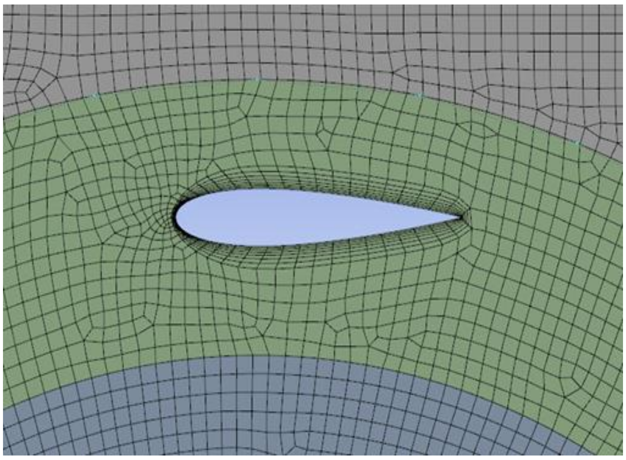


Fig. 3. Mesh view near the blades

3. Results
3.1 Single Darrieus

The experimental testing provided valuable insights into the aerodynamic behavior and performance of single Darrieus wind rotor. The blade radius is 10 cm for the single blade configuration. The power coefficient (Cp) values obtained from the experiments with respect to tip speed ratio are summarized in Figure 4. The experimental results for the single blade configuration show power coefficient values ranging from 0.05 to 0.1.

Tip speed ratio is a crucial parameter that characterizes the performance of a Darrieus VAWT. In this paper, TSR falls within the range of 0.1 to 0.2. This deviation from the normal range is primarily attributed to the size and solidity of the model used in the experiments. The relation between solidity and airfoil dimensions is in Eq. (8) [28]:

$$\sigma = \frac{bc}{R} \tag{8}$$

Present solidity value is calculated to be 1.05 and the corresponding TSR for the maximum power coefficient is reported to be 0.15592. In reference [23] at the same solidity value of 1.05, tip speed ratio for the maximum power coefficient is found to be 0.16 (Figure 5)

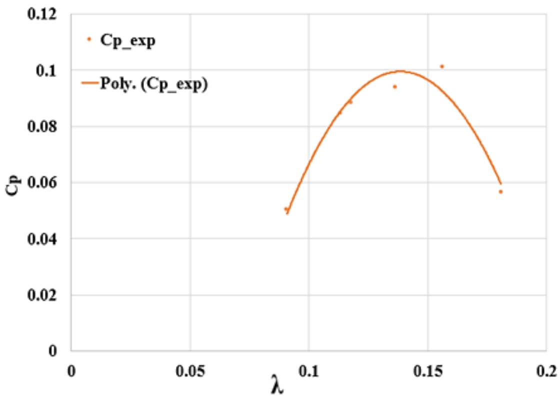


Fig. 4. Experimental results for single blade (at a 10 cm radius)

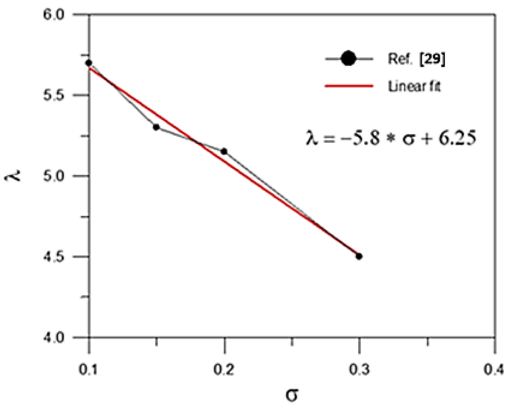


Fig. 5. Solidity and tip speed ratio [29]

Simulations visualized air flow velocities around the rotor at 26 m/s. Contour plots depicted velocity variations across blades and surroundings. Figure 6 shows velocity distributions at 26 m/s: θ = 0° and 90°. θ = 0° demonstrated efficient energy use, proper blade alignment and maximized turbine efficiency. While θ = 90° led to flow separation, hampering energy utilization. θ = 180° also yielded favorable results. θ = 270° had minor impact on power generation and efficiency due to blade's end position.

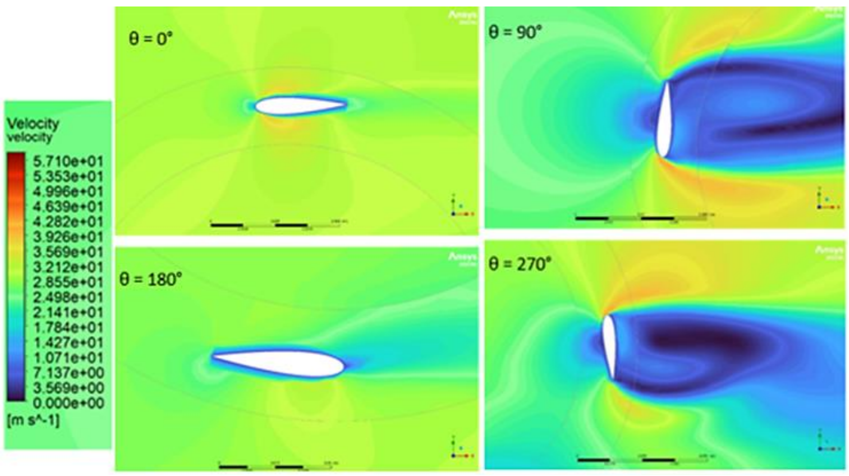
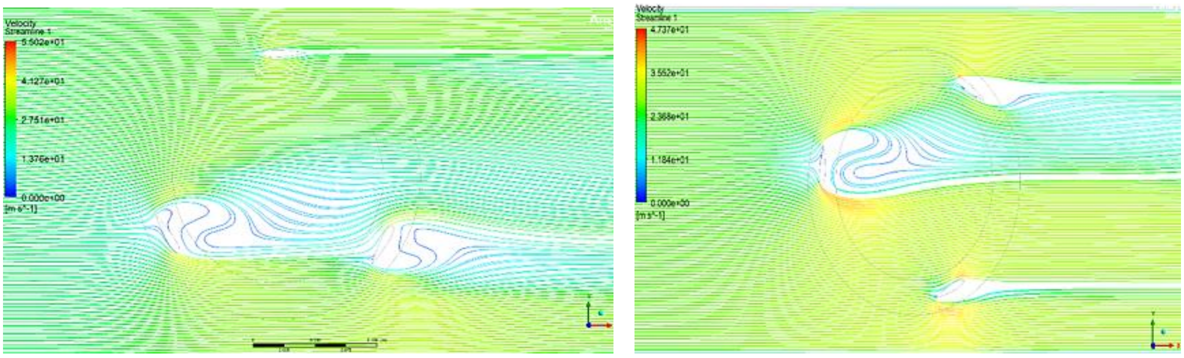


Fig. 6. Air flow velocity distributions at air velocity of 26 m/s, at θ = 0°, θ = 90°, θ = 180°, θ=270°

Streamlines visualization colored by velocity magnitude provides valuable insights into the flow characteristics at various blade positions. At 0°, it offers a depiction of the flow pattern near the leading edge of the blade. At 90°, it provides a distinct perspective, when the blade is perpendicular to the wind flow, Figure 7.

A validation process is conducted by comparing power coefficient values of the numerical results with the corresponding experimental data for the single blade configuration. Validation analysis, Figure 8, revealed that the error range between the numerical and experimental results are approximately less than 20%, which is considered reasonable for such complex aerodynamic simulations. Moreover, the observed trend in the power coefficient values from the numerical simulations are found to be compatible with the experimental results.



(a) (b)

Fig. 7. Streamlines colored by velocity magnitude for single blade (a) θ = 0° (b) θ = 90°

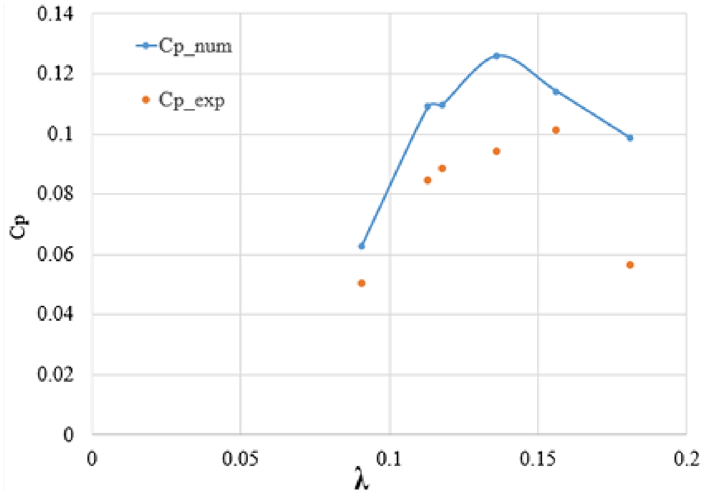


Fig. 8. Validation between the numerical and experimental results

3.2 Double Darrieus

Double blade configuration where the inner blade changes its position from the inner shaft to the outer blade by 1 cm step is shown in Figure 9. This configuration is discussed for a modified flow pattern and to potentially affect the overall aerodynamic behavior of the wind turbine. The power coefficient values were evaluated. The outer blade remained at a distance of 10 cm from the rotor.

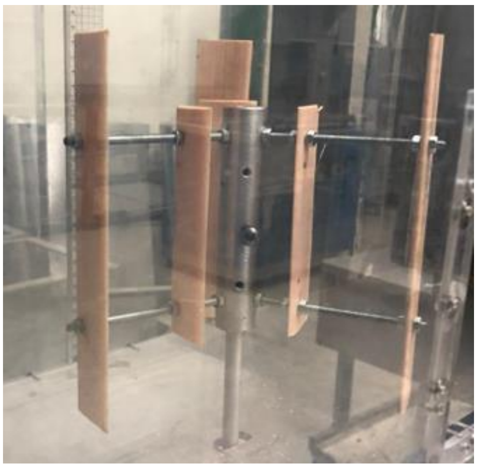


Fig. 9. study experimental configuration of Double Darrieus wind turbine

The power coefficient values versus TSR for different inner blade distances (L) are presented in Figure 10. Power coefficient values vary for each inlet blade distance, ranging from 0.016711708 to 0.252215436. Results showed that the most efficient position coincided with 40% of length at 4 cm from rotor, and 3 cm from the rotor. The power coefficient revealed influence of blade positioning on the turbine's performance. Its values varied with the distance of the inlet blades from the rotor, indicating the importance of blade placement for maximizing power extraction. The results showed that the power coefficient generally increased as the inner blade distance decreased especially from 30% to 40% distance from the rotor. This finding highlights the significance of optimizing the design and configuration of the Darrieus wind turbine for improved performance.

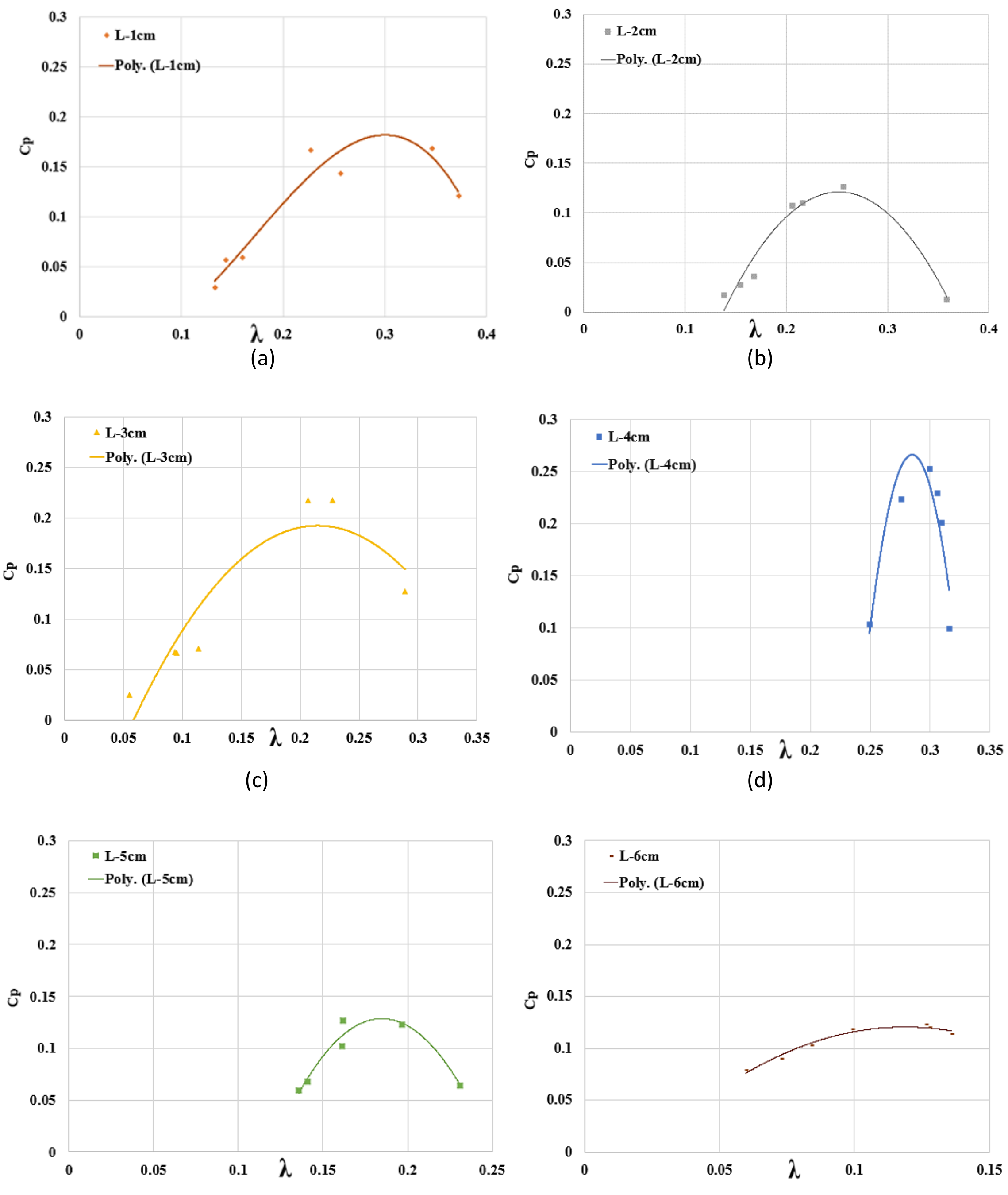


Fig. 10. Power coefficient values (a) L=1 (b) L=2 (c) L=3 (d) L=4 (e) L=5 (f) L=6

Numerical results are obtained from the simulations of the double blade configuration of the Darrieus wind rotor. Contour depict air flow velocities around the double-blade setup at 26 m/s, Aligning blades with wind flow (θ = 0°) results in even velocity distribution, ensuring effective wind energy use (Figure 11). Conversely, perpendicular blades (θ = 90°) lead to flow separation, wake effects, and decreased energy utilization. Notably, θ = 180° presents efficient configuration, while θ = 270° minimally affects power generation despite flow separation. Visualization of streamlines colored by velocity magnitude as illustrated in Figure 12, it provides valuable insights into the flow characteristics of a double-blade Darrieus vertical axis wind turbine (VAWT) at various blade positions. Examining the streamlines for the blade positioned at 0° offers a depiction of the flow pattern near the leading edge of the blade. Streamlines corresponding to the blade positioned at 90° provide a distinct perspective, revealing the flow behavior around the trailing edge of the blade.

Finally, referring to improvement achieved by the double blade configuration and as mentioned in Figure 10(e) where the blade at 5 cm from the rotor and at a speed of 26 m/s, the result for single blade power coefficient (Cp) is 0.108, and the results for Double blade power coefficient (Cp) is 0.117, this indicates Improvement of 6.7% between single blade and double blade numerical cases.

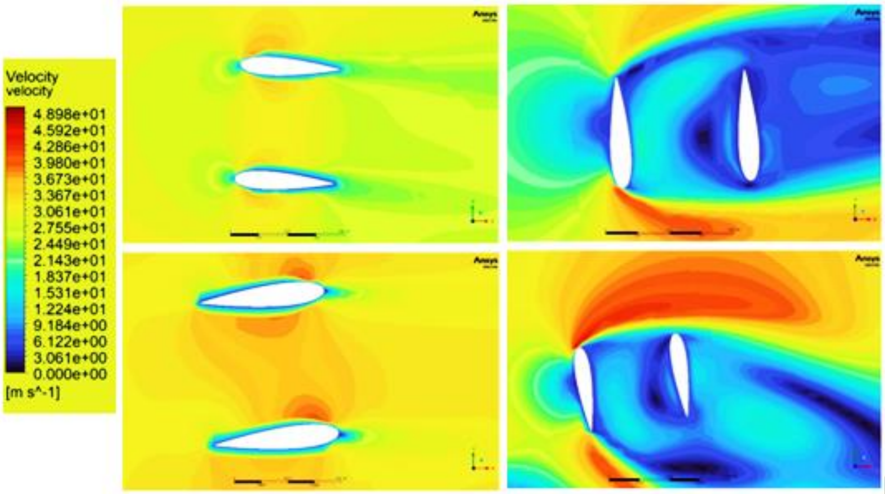


Fig. 11. Air flow velocity distributions at an air velocity of 26 m/s, at θ = 0°, = 90°, θ = 180°, θ=270°

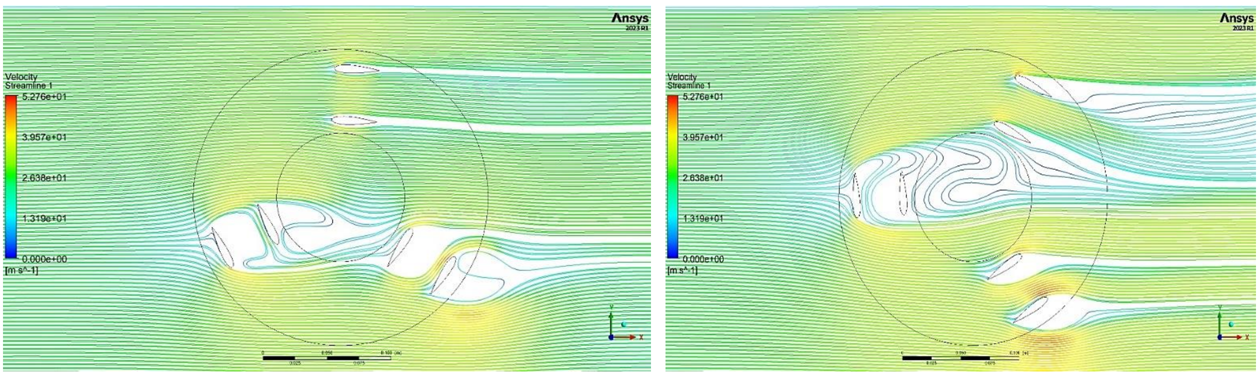


Fig. 12. Streamlines colored by velocity magnitude for double blade, at θ = 0°, θ = 90°

4. Conclusions

This study has explored the potential of wind energy as a clean and renewable source of power, highlighting its importance in addressing environmental concerns on fossil fuels. The experimental and numerical study conducted on the double-blade Darrieus wind turbine has provided valuable insights into its performance and flow characteristics.

i. The comparison between the numerical and experimental results for the single-blade Darrieus turbine demonstrated a reasonable level of agreement, with less than 20% error. validating the effectiveness of both approaches.
ii. The analysis of power coefficient and tip speed ratio has shed light on the influence of blade positioning and design parameters on turbine performance, results showed that the most efficient position coincided with 40% and 30% of the length.
iii. The comparison between single blade and double blade numerical cases Results showed an Improvement of 6.70% for Double Blade.

The insights gained from the experimental and numerical study can be utilized to optimize the design, operation, and integration of double-blade Darrieus turbines for enhanced wind energy utilization.

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