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Two Dimensional Computational Fluid Dynamic Analyses to Study the Effect of Blade Number and Solidity on the Performance of a Straight Bladed Darrieus Vertical Axis Wind Turbine

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ABSTRACT:*Solidity of vertical axis wind turbines (VAWTs) is an important design parameter that affects its aerodynamic performance at different tip speed ratios. Solidity depends on the number of blades, airfoil chord length and turbine diameter. In this study a computational fluid dynamic analysis is performed using commercial Fluent ANSYS code in order to investigate the effect of the number of blades and solidity at different values of tip speed ratios on the performance of a two dimensional straight bladed fixed pitch VAWT for the reason to obtain an optimum power curve. Two, three, four and five bladed turbines performances are investigated in addition to changing the chord length for a three bladed turbine. The domain size, mesh and turbulence model sensitivity studies are done to choose an appropriate numerical model and number of cells to improve the solution results. Two turbulence models k-omega SST and transition SST are used to illustrate the transition in the boundary layer near the airfoils. Validation of the numerical model is done by comparing the results of the calculated power coefficient with the available published wind tunnel data where acceptable results are shown for the transition SST model. The numerical calculation resulted in high values of power coefficient with lower solidity values for a three bladed turbine.*

KEYWORDS: *Computational Fluid Dynamics; ANSYS Fluent; Straight Blade Vertical Axis Wind Turbine; Power Coefficient; solidity; Fixed Pitch VAWTs.*

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I. INTRODUCTION

The increase of the consumption of energy resources and the depletion of fossil fuels turned the attention towards the use of alternative energy resources. Wind power is one of the most promising renewable sources of energy. Efforts have been made in recent decades to benefit from wind power as a reaction to the state of the growing demand of energy. Power is extracted from wind by either horizontal or vertical axis wind turbines. In urban areas continuous fluctuation in flow direction and levels of turbulence enhances the performance of VAWTs [1]. Most designers and manufacturers are interested in developing the capabilities of small sized VAWTs, especially with straight blades because of their easy design and low manufacturing costs [2].

To improve the performance of VAWTs computational Fluid dynamics (CFD) capabilities are adopted. Simulation of the turbine blade rotation and its transient flow field is presented by a discretized computational domain. The domain consists of two sub domains: a rectangular outer zone, and a circular subdomain concentric with the turbine rotational axis [3].

Using the 4-equation transition SST turbulence model in the numerical solution improves near wall treating, and permits more adaptable grid generation process that decreases the boundary layer separation caused by adverse pressure gradient [4]. In an analytical study to choose a suitable turbulence model, it was found that the transition SST model was capable to detect flow parameters at low and high angles of attack [5], [6].

The performance of VAWTs is affected by the value of solidity and tip speed ratios (λ) [7]. Solidity depends on the number of blades (N), airfoil chord length (C) and turbine radius (R), and it is defined as:

$$\sigma = \frac{N\,C}{2\pi R} \qquad (1)$$

A study of solidity effect on the performance of a three bladed VAWT having a 2 meters diameter done by changing the chord length from 0.15 to 0.3 meters resulted in higher turbine performance at low solidity values [8]. Increasing solidity, the maximum power coefficient value decreases, and the corresponding tip speed ratio shifts to a lower value [9]. The number of blades of the turbine is an important factor that affects the turbine performance. Increasing the number of blade leads to an increase of the resultant useful aerodynamic forces to increases the turbine torque [10]. However, upstream blades wake interacts with the downstream blades leading to unfavorable consequences of flow separation and blade stall [11].

The aim of this study is to investigate the effect of the number of blades and solidity at different tip speed ratios on the performance of the two-dimensional VAWT in order to obtain an optimum power curve. Numerical simulations are performed to solve the unstable Reynolds average Navier Stokes (URANS) equations using ANSYS fluent, the turbulence parameters are solved using k-omega SST and transition SST models to illustrate the transition in the boundary layer near the airfoils. The results are compared with available experimental data.

II. NUMERICAL MODEL

2.1. Turbine Geometry:

The present study includes numerical analysis of the aerodynamic behavior of VAWT at different tip speed ratio (λ=1.6 to 3.2) for an inlet wind velocity of 9 m/s. The geometric specifications of the fixed pitch VAWT are illustrated in Table (I). The rotor consists of three straight blades spread equally around the azimuth angle with a spacing of 120^{o} between consecutives blades. Each blade is attached to the turbine rotor with a spoke fixed at quarter chord distance from the leading edge of the airfoil [12] Figure (1) shows the velocity triangle and aerodynamic forces on the turbine blade at an arbitrary azimuth position.

***Table I.* VAWT Geometrical Parameters**

Airfoil	NACA 0021
Number of Blades (N)	3
Turbine Rotor Diameter (R) (m)	1.030
Turbine Height (H) (m)	1.414
Airfoil Chord (C) (m)	0.0858
Shaft Diameter (m)	0.05
Freestream Velocity (V_∞) (m/s)	9

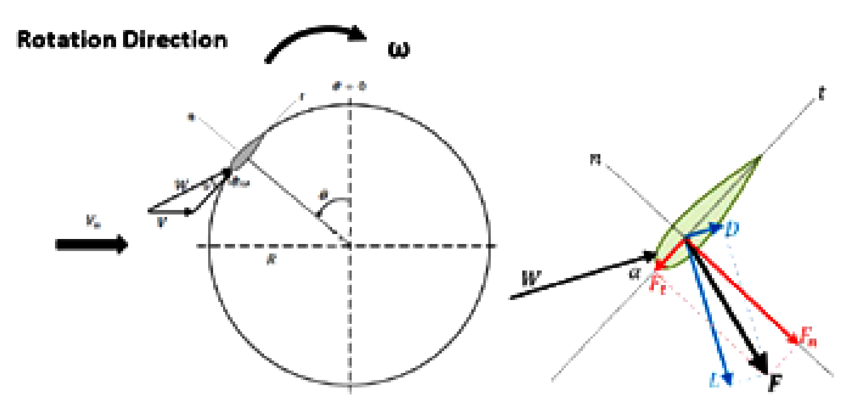


Figure 1: Schematic of VAWT Velocities Triangle and Force Components

2.2. Aerodynamic Model of VAWTs

The relative wind speed (W) and angle of attack (α) changes during revolution along the azimuth angles (θ) [13]:

$$\mathrm{W} = \mathrm{V}\sqrt{(\frac{\lambda}{\mathrm{V}/\mathrm{V}_\infty} + \cos\theta)^2 + \sin^2\theta} \qquad (2)$$

$$\alpha = \tan^{-1}[\frac{\cos\theta}{\sin\theta + \lambda}] \qquad (3)$$

Where:

V is the local induced velocity

λ is the tip speed ratio ($\lambda = \frac{R\omega}{V_\infty}$)

ω is the angular velocity

Resolving the aerodynamic forces in the direction tangent and perpendicular to the airfoil path results in tangential force ($\mathrm{F_t}$) and normal force ($\mathrm{F_n}$) determined from the lift coefficient ($\mathrm{C_l}$) and drag coefficient ($\mathrm{C_d}$) as following:

$$\mathrm{F_t} = \mathrm{C_t}(\frac{1}{2}\rho \mathrm{A_p} \mathrm{W}^2) \qquad (4)$$

$$\mathrm{F_n} = \mathrm{C_n}(\frac{1}{2}\rho \mathrm{A_p} \mathrm{W}^2) \qquad (5)$$

$\mathrm{C_t}, \mathrm{C_n}$ are tangential and normal aerodynamics force coefficients, ρ is the air density, $A_p = CH$ is the blade planform area:

$$\mathrm{C_t} = \mathrm{C_l}\sin\alpha - \mathrm{C_d}\cos\alpha \qquad (6)$$

$$\mathrm{C_n} = \mathrm{C_l}\cos\alpha + \mathrm{C_d}\sin\alpha \qquad (7)$$

The average tangential force $\overline{F_t}$ is calculated as follows:

$$\overline{\mathrm{F_t}} = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{F_t}(\theta)d\theta \qquad (8)$$

The dynamic torque (Q) and turbine output power (P_{out}) equations:

$$Q = N\mathrm{R}\overline{\mathrm{F_t}} \qquad (9)$$

$$P_{out} = Q\omega \qquad (10)$$

The power coefficient (C_P) is characterized as the proportion of turbine output power to the power possessed from the wind as expressed by:

$$C_p = \frac{P_{out}}{\frac{1}{2}\rho A_p V_\infty^3} \qquad (11)$$

From the power and torque equations, it can be see that the developing of the power intensity of VAWTs is affected mainly by the flow angle which affects the value of the tangential force.

2.3. ***The Domain Size***

The cross-section of the blade is constant along its span; a 2D model of the turbine of diameter (D) is used for the numerical solution. A sliding mesh approach is adapted, where an interface is created between a circular rotating domain of diameter (1.2D) and a fixed rectangular domain as shown in figure (2) where the choice of the domain size considers the wall influence on the performance of wind turbine. A sensitivity study of the domain size is implemented by changing the rectangular length to 30D, 45D, and 60D and changing the width to 20D, 30D, and 45D. Table (II) shows the power coefficients results for three different domains sized, where the domain size (45D × 30D) is chosen for further computations performed in this study**.**

***Table II.* Sensitivity of Domain**

Dimensions of domain	Power coefficients
(30D × 20D)	0.3933
(45D × 30D)	**0.3876**
(60D × 45D)	0.3862

The left boundary of the rectangular domain is represented by a uniform air velocity inlet boundary condition (x-component=9 m/sec), the right boundary is defined as pressure outlet boundary condition, and the upper and the lower boundaries are described by symmetry with a no-slip wall condition. The exterior diameter of the revolving district is 1.2D and its interior diameter is 0.8D [12].

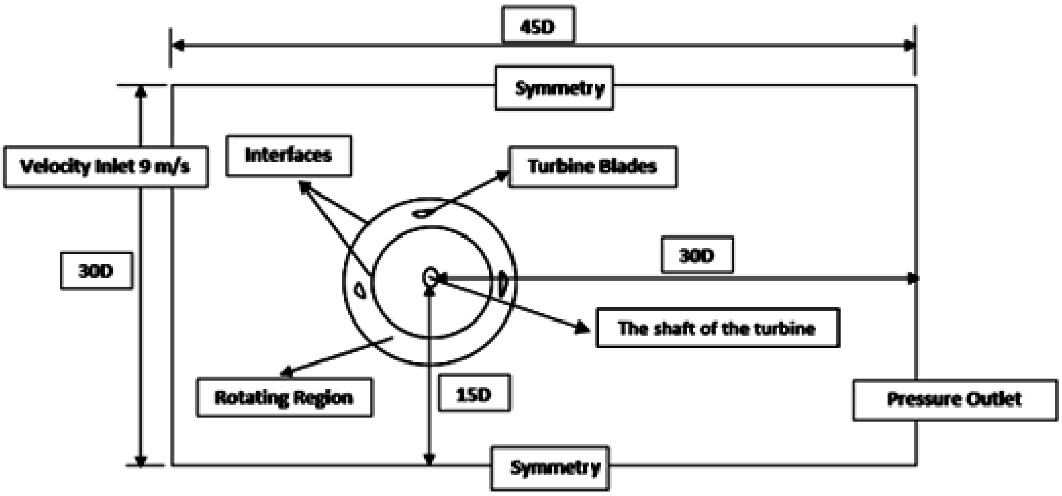


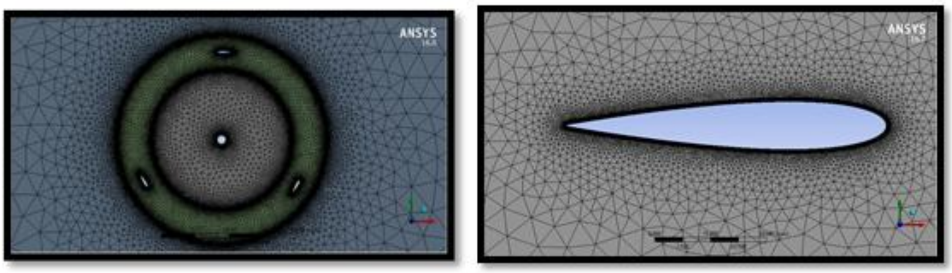
Figure 2: Schematic of the Best Domain for the Examined VAWT.

2.4. Grid Sensitivity Study

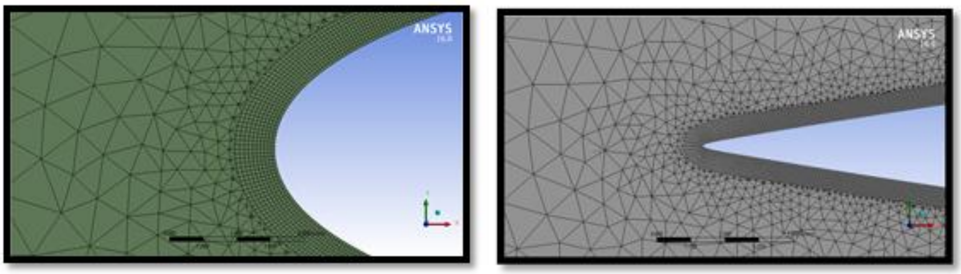
The sliding mesh method is utilized to study the unsteady flow caused by the revolution of the turbine blades. The boundary layer around the airfoil is characterized by an inflation formed from parallelogram cells of 10 levels with a maximum thickness of 1 mm and a growth rate of 1.1. The mesh in other regions of the domain is assigned to be triangular cells. Five grid levels are examined such that each level is approximately twice the number of cells of the previous. The moment coefficients are compared as shown in the table (III) and grid level 3 is chosen to proceed with in other calculations throughout the study. The mesh configuration is displayed in Figure (3).

Table III. Grid Sensitivity Study

Name	Number of cells	Cm	Cp
Mesh 1	49558	8.38E-03	0.023045
Mesh 2	84108	0.141	0.38775
Mesh 3	**165924**	**0.161**	**0.44275**
Mesh 4	271812	0.16	0.44
Mesh 5	403490	0.162	0.4455



(a): Near the rotating core (b): Near the airfoil



(c): Leading edge of airfoil (d): Trailing edge of airfoil

Figure 3: Computational Grid

2.5. Solver Settings and Turbulence Model:

The two-dimensional unsteady Reynolds-Averaged Navier-Stokes (URANS) equations are solved using ANSYS-Fluent 16.1 software. The Simple algorithm for pressure-velocity coupling is applied employing a second order upwind scheme [14], [15], and [16]. The simulation starts with a steady first to install the flow domain to sensible parametric values, then a transient flow simulation is achieved using the sliding mesh model regarding a time step that represents one degree azimuth revolution taking into consideration different tip speed ratios:

$$\Delta t = \frac{1}{(RPS * 360)} \qquad (12)$$

For turbulence modeling, two models are adopted, the two equations shear stress transport (SST) k-ω model and the four equations transition (SST) model. Iteration is done for twenty cycles at different tip speed ratios, and the torque coefficient is obtained by averaging the results for the last five cycles. The power coefficient is calculated by:

$$C_p = C_m \times \lambda \qquad (13)$$

III. RESULTS AND DISCUSSION:

3.1. Numerical Model Validation

In order to confirm the validity of the numerical model, the computed results are compared with available experimental data [17]. The comparison demonstrated in figure (4) shows that the results are in consistence. The results predicted by the transition SST model for the values of C_p are closer to the experimental data compared to those predicted by the k-omega SST turbulence model. The power coefficient is calculated at a range of tip speed ratio of $1.6 \leq \lambda \leq 3.2$. Figure (5) shows the velocity contours around the turbine blades. The colored contours show a significant region of high kinetic energy represented by high values of flow velocity on both sides past the turbine blades.

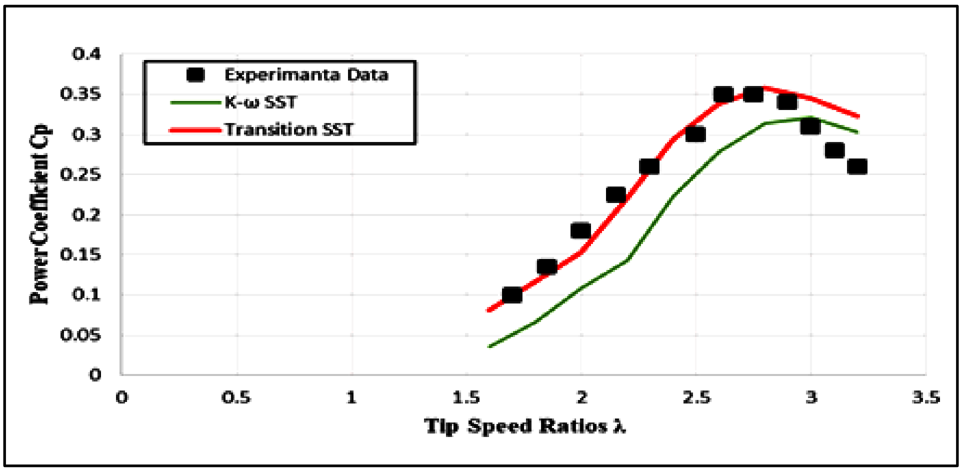


Figure 4: Power Coefficient (C_P) at different Tip Speed Ratios

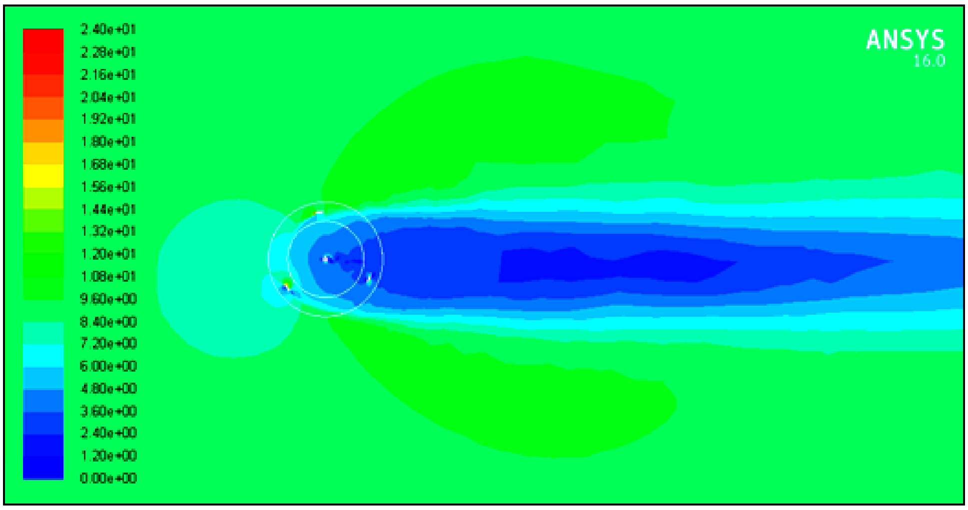


Figure 5: Velocity Contours around the VAWT

3.2. Effect of the number of blades on the VAWT Performance

Different turbine configurations with two, three, four, and five blades are studied in order to show the effect of the number of blades on the performance of the VAWT. Figure (6) demonstrates the comparison between the power coefficient results at different tip speed ratios.

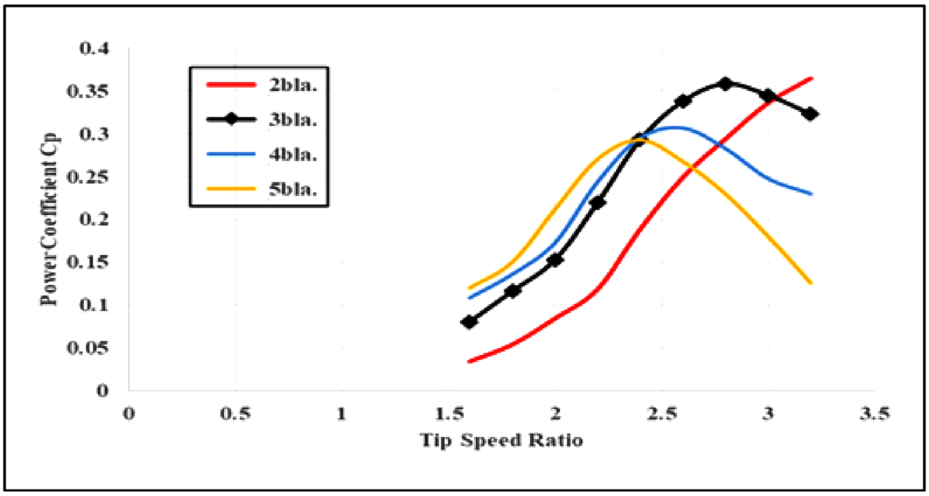


Figure 6: Effect of the number of Turbine blades on the Performance at Different tip Speed ratios

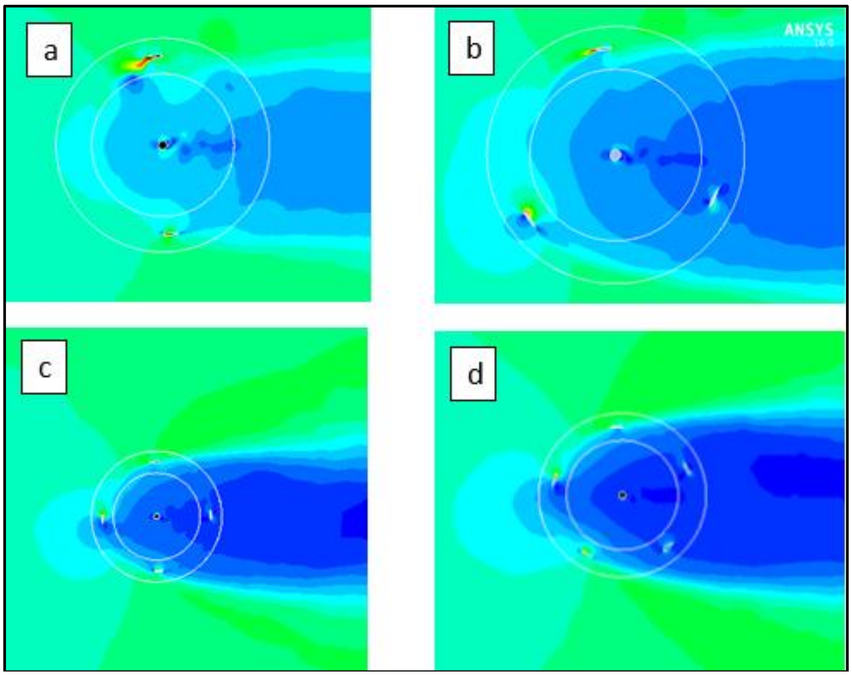


Figure 7: Velocity Contours for (a) Two blades, (b) Three blades, (c) Four blades, and (d) Five blades

The four and five blade turbines resulted in lower peak values of C_p compared to the two and three blade turbines due to the effect of up-stream blades wake interaction with the down-stream blades as shown in the velocity contours in figure (7). The two blades turbine results in high values of power coefficient at only high tip speed ratios. The three blades turbine is privileged on the two blades turbine by its high values of power coefficient for a wide range of tip speed ratios, with a peak value of 0.35; in addition, increasing the number of blades enables the self-starting at low wind velocities.

3.3. ***The Effect of the Solidity on the VAWT Performance***

For the three blades turbine configuration, the solidity effect is studied by changing the chord length to 60, 76, 85.8, 100 and 120 mm such that two values are chosen above and below the validated case study. The results in figure (8) show that increasing the chord length (100 and 120 mm) results in a lower peak value for C_p and a shift in its position corresponding to lower value of λ. However, decreasing the chord length (60 and 75 mm) results in a lower peak value for C_p and a shift in its position corresponding to higher value of λ. The results of the case study (C=85.8 mm) are appropriate for high C_p at a wide range of λ that offer a self-starting capability.

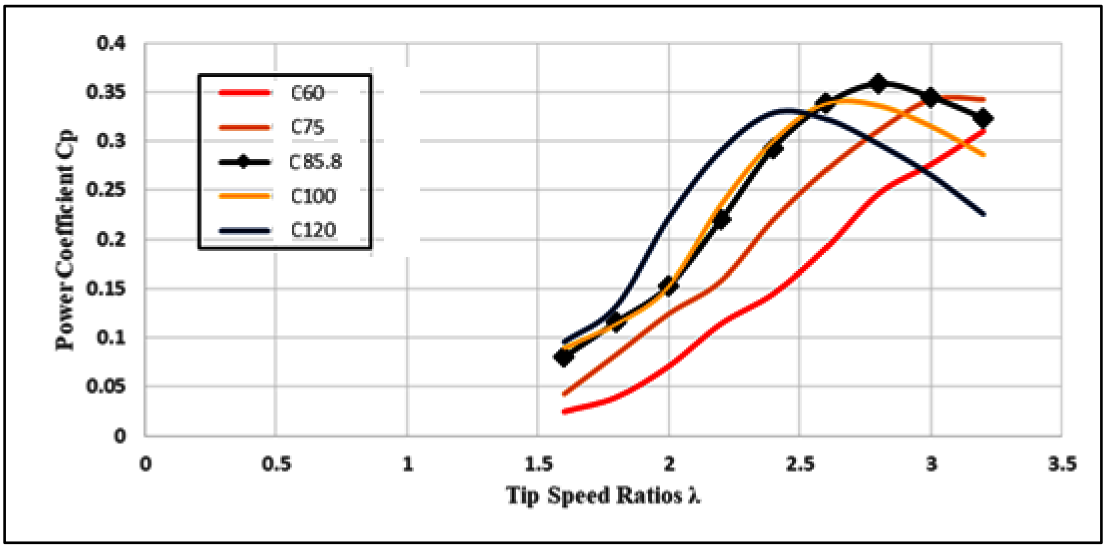


Figure 8: Effect of Solidity of the VAWT Performance at different Tip Speed Ratios

IV. CONCLUSIONS

A numerical study for the effect of chord length, and number of blades on the efficiency of VAWTs is implemented. The numerical model is validated by comparing the results of solving a case study with the available wind tunnel measurements at different tip speed ratios. Different turbine configurations of two, three, four and five blades are solved in addition to changing the chord length for the three blade configuration. The numerical results showed that:

- A three blade turbines has the highest values of power coefficient for a wide range of tip speed ratios, with the highest peak value of C_p of 0.35 at $\lambda=2.8$, in addition that enables the self-starting at low wind velocities compared to two blades turbines.
- Increasing the blade solidity by increasing the chord length of the validated case study to 100 and 120 mm results in a lower peak value for C_p and a shift in its position corresponding to lower value of λ. However, decreasing the blade solidity by decreasing the chord length to 60 and 75 mm results in a lower peak value for C_p and a shift in its position corresponding to higher value of λ.
- The results of the validated case study for both number of blade and solidity effects shows highest values of C_p at a wide range of λ with an appropriate number of blades that offers a self-starting capability without being affected by wake interaction between blades.

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