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Experimental and Numerical Investigation on the Performance of Straight-Bladed Vertical Axis Wind Turbine by Adding Cavities to it Structure

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ABSTRACT

As the prices of the fuel and power had fluctuated many times in the last decade and new policies appeared and signed by most of the world countries to eliminate global warming and environmental impact on the earth surface and humanity exciting, an urgent need appeared to develop the renewable energy harnessing technologies on the short-term and long-term and one of these promising technologies are the vertical axis wind turbines, and mostly the combined types. The purpose of the present work is to combine a cavity type Savonius with straight bladed Darrieus to eliminate the poor self-starting ability for Darrieus type and low performance for Savonius type and for this purpose, a three-bladed Darrieus type with symmetrical S1046 airfoil was tested experimentally and numerically at different wind speeds (4.5 m/s, 8 m/s and 10 m/s) and it showed a poor self-starting ability at low wind speed although its higher performance at high wind speed. However when adding the cavities in two setup configuration and testing it at the same conditions, it was found that when adding the cavities as reversed cups in the core of the turbine, the performance increased and the power coefficient reached a maximum value at 10 m/s wind speed and it was observed to be 0.0914 , but when the solidity increased by adding three cavities, the performance was higher at low wind speed (4.5 m/s) but it tragically decreased at higher wind speed which indicates that the performance depends on the solidity and the turbine configuration. On the other hand, the numerical simulation showed a good match with the experimental results although it under-predicted the performance.

Keywords: Vertical Axis Wind Turbine, Straight Bladed Darrieus, Cavity Type Savonius, Power Coefficient, Torque Coefficient.

أستقصاء عملي و نظري في أداء التوربين الهوائي ذو المحور العامودي و الريش المستقيمة بأضافة التجاويف الى هيكله

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الخلاصة

بسبب تذبذب اسعار الوقود و الطاقه في العقود الاخيرة لعدة مرات و ظهور لوائح و تعليمات جديده تم التوقيع عليها من قبل معظم دول العالم لتقليل ظاهرة الاحتباس الحراري و التأثير البيئي على سطح الارض و استمرارية وجود الجنس البشري، ظهرت حاجة ملحة لتطوير تكنولوجيا استخلاص الطاقات المتجدده على المدى القريب و البعيد و احدى هذه التكنولوجيا الطموحه هي توربينات الهواء ذو المحور العامودي و خاصة الانواع المركبه. الغرض من هذا العمل هو تركيب نوع التوربينات سافونيوس ذا الريش المجوفه مع التوربين نوع داريوس ذو الريش المستقيمه لتقليل ضعف قدرة التشغيل الابتدائي لتوربينات داريوس و ضعف الاداء لتوربينات سافونيوس و لهذا الغرض تم اختبار داريوس مع ريش مستقيمه من النوع S1046 عملياً و نظرياً عند سرع رياح مختلفة (4.5 m/s, 8 m/s and 10 m/s) و قد اظهر قدرة ضعيفة على الدوران الابتدائي عند سرع الرياح الواطئه رغم الاداء العالي عند سرع الرياح العاليه و لكن عند اضافة الريش المجوفة بتشكيلين مختلفين و اعادة الاختبار عند نفس الظروف، وجد انه عند اضافة تجويفين متعاكسين في قلب التورباين ان الاداء و معامل القدرة قد ازدادا الى اقصى حد عند سرعة رياح 10 m/s و قد وجد معامل الاداء بأنه 0.0914، ولكن عند زيادة الصلاده بأضافة ثلاث ريش مجوفة ، الاداء كان عالياً عند سرع الرياح الواطئه (4.5 m/s) لكنه انهار بشكل عالي عند سرع الرياح العاليه و هذا دل على ان اداء التوربين يعتمد بشكل اساسي على الصلاده و على التشكيل. على الجانب الاخر، المحاكاة الرقميه اظهرت تطابقاً جيداً مع النتائج العمليه رغم توقعها اداءً اقل.

الكلمات الرئيسية: توربين هوائي ذو محمور عامودي، داريوس ذو الريش المستقيمه، سافونيوس ذو الريش المجوف، معامل القدرة، معامل العزم.

1. INTRODUCTION

Renewable energy is the world word of mouth today, as indeed it reached 18% of the world electricity generation and its promising ratio compared to the last two decades. (**Hussein T. Al-Najjar, 2015**).

In spite of the domination of the Horizontal Axis Wind Turbines (HAWTs) on the worldwide electricity generation, Vertical Axis Wind Turbine (VAWT)s is the most likely to use in the future, mostly because of the lack of open areas near cities and low wind speed. In addition, despite the low power coefficient and a low capacity factor of the VAWTs, it has great and enormous advantages, such as low construction cost and low maintenance cost because of the generator and gearbox on the ground. Also, no need for yaw mechanism or any force or natural direction pointers since they catch the wind in any direction and ability to take advantages of gusty and turbulent winds. Moreover, less noise and avian problems and of course they can be gathered more closely in wind farms so increasing the generated power per unit of land area (**Ragheb, 2015).**

Day after day, a new design of VAWTs appears and a new combination of Darrius and Savonius types are published and manufacture, especially because of its low cost and its ability to give the advantages of both types such as higher dynamic torque for Darrieus type and higher static torque of Savonius type. Also because it eliminates the most common disadvantages of both types such as the low starting torque of Darrieus wind turbine and low dynamic performance of Savonius wind turbine (**EWEA, 2009).**

A lot of researches were done, most of them were numerically and mostly on the combination of conventional types of Darrieus and Savonious as four bladed Darrieus with two reversed cups Savonious as it done by (**Yan Li et.al, 2010**) numerically with wind turbine that was consisting

of four blades H-rotor with a radius of 900 mm and two reversed half cups Savonius rotor with a radius of 300 mm and zero overlaps. The study was in two dimensions and conducted by a finite volume method with instructed grid and incompressible steady flow. The domain was 4000 m×4000 m and the wind speed was fixed at 12 m/s and model final mesh was consisting of 100,000 elements and it was found that the static torque showed a high increment corresponding to Straight-Bladed Vertical Axis Wind Turbine (SB-VAWT) as it increased from 0.02 at 30° to 0.22 at the same azimuthal angle which about 10 times than the value of SB-VAWT.

On the other hand fewer researchers used the experimental methods as it needs big facilities with specific instruments but the published researches showed a great results in the performance as **(Bhuyan and Biswas, 2014)** when they studied experimentally the performance difference between the H-rotor Darrieus with three bladed S818 cambered airfoil wind turbine and the combined Savonius- Darrieus wind turbine at different overlap ratio and the results showed that the static torque coefficient increased in the hybrid turbine case and it reached a maximum value of 0.4 at overlap of 0.175 and the maximum power coefficient was obtained in the hybrid case at λ=2.29 and Reynolds number of 1.92×10^+5 at 10m/s wind speed and overlap of 0.15 and it was found to be 0.34, and followed by power coefficient equal to 0.28 for simple H-rotor at λ=2.42 at the same wind speed.

Also **(Louay A. Rasheed, 2018)** studied the combination of Savonius wind turbine with traditional ventilator to increase the ventilation rate through increasing the startup torque and rotational speed and it found that the new design achieved an increase in the rotational speed than the traditional ventilator and its reached 107 rpm and that's lead to a better ventilation for the closed rooms.

2. MODEL DESIGNING

As the turbine was tested by open-circuit blowing wind tunnel, there is no blockage ratio or wall effect to consider when designing the wind turbine as it frontal area just must not exceed 100% of the area of the output section of the wind tunnel so the flow will cover the turbine entirely or moving it in a distance from the output section after ensuring the flow at this distance is fully laminar and cover the turbine. **(Gawade, et.al 2015)**, **(Rassoulinejad-Mousavi, et.al 2013)**.

For the studied turbine, the frontal area did not exceed 35% of the area of the wind tunnel outlet and it was equal to 30.186% that gave the turbine a frontal area of 6,250 mm² in comparison with the wind tunnel outlet area which is 207,025 mm² according to the blockage ratio relation below:

Blockage Ratio (B.R)=Frontal Area of The Wind Turbine / Cross-Sectional Area of the outlet of
   the wind tunnel   (1)

Also the aspect ratio (A.R) that was chosen is equal to 1 according to **(Singh,et.al, 2015)** and for the blade selection, the selected airfoil was S1046 and it was based on the previous literature survey **(Mohamed, 2012),** (Singh, Biswas and Misra, 2015) and since the number of the blades was chosen to be three (Singh, Biswas and Misra, 2015), the resultant chord length was equal to 83.333 mm according to the solidity equation below:

$$\sigma = N \times \frac{C}{D}$$ (2)

While the cavities main design were also depending on the previously studied literature **(Ahmed Y Qasim et.al, 2014)** which it is half hexagonal, and the height of it were selected to be the same as the height of the blades and the width was according to H/D ratio that calculated from the studied

literature which is equal to 3.57 **(Ahmed Y Qasim et.al, 2011)** and that leads to the width of the cavities equal to 70 mm.

3. MODEL DRAWING AND FABRICATION

The three turbines models were designed by Solidworks 2017 according to the previous calculation. The models were created first as 2D drawings with 1*10-6 error percentage then all of the turbine's components were extruded separately to the required heights and transformed to one body to avoid any problems that may cause when exporting it to the numerical simulation software as shown in Fig. (1), (2) and (3).

The three blades and the cavities were printed from Polylactic acid (PLA) using high accuracy three-dimensional printer (3D printer) (ANYCUBIC i3) then polished and finished by sandpapers then it was painted with standard white cars dye.

The upper and lower Structures were made from Acrylic Fiber through cutting it by high accuracy laser machine (KB-K3020).
The Turbine was held by a costumed structure that has been designed by Solidworks with dimensions of (3 mm×40 mm×80 mm) (T×W×L) and formed from steel to form turbine holder which have the inner dimension of 650 mm×650 mm and adjustable holding legs that give it a minimum height of 1800 mm and a maximum height of 1950 mm.
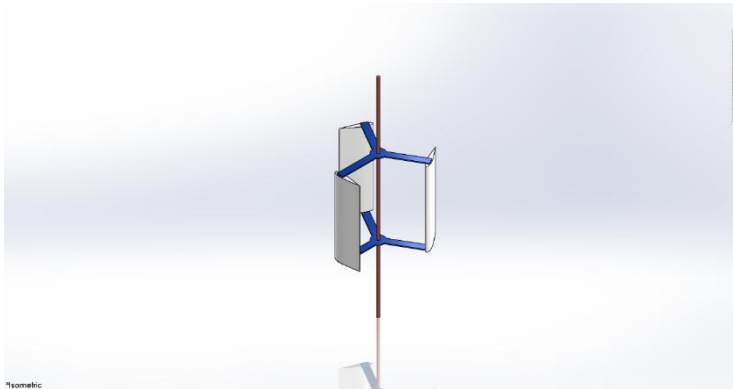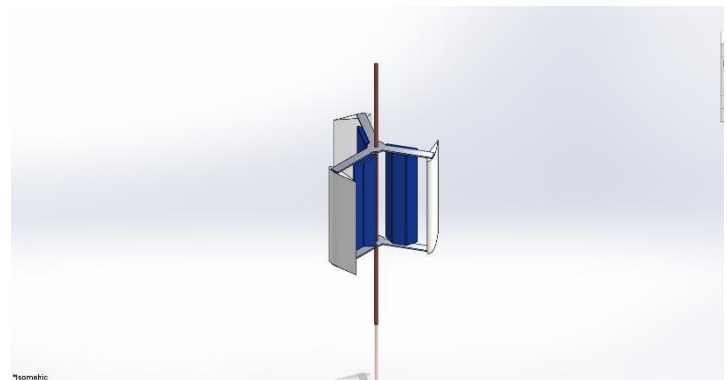

Figure 1. 3D Design of SB-VAWT
by Solidworks.

Figure 2. 3D Design of 3Cs-SB-VAWT
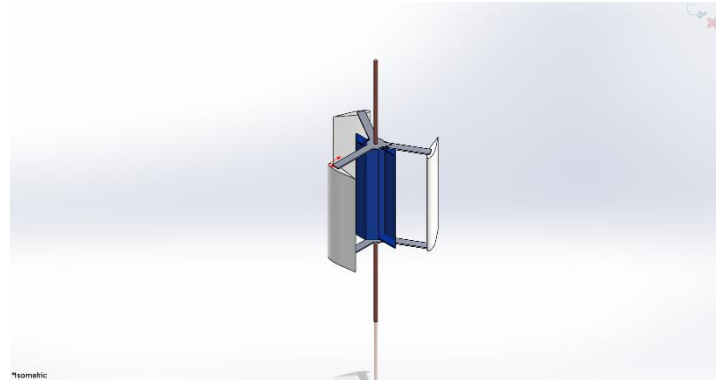by Solidworks.

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Figure 3. 3D Design of 2Cs-SB-VAWT by Solidworks.

5. EXPERIMENTAL PROCEDURE:

The turbines were tested with blowing wind tunnel that generates three different wind speeds (4.5 m/s, 8 m/s and 10 m/s) and it had been using an anemometer to measure the wind speed and tachometer to measure the revolution per minute and the turbine was coupled directly to a 10 Watt DC motor. Three cases of experimental runs where conducted; the first case was the SB-VAWT without cavities at three values of wind speed, the second case was the SB-VAWT with two reversed cavities and the electrical generator at three values of wind speed and the third and the final case was the SB-VAWT with three cavities and the electrical generator at three values of wind speed as shown in Fig. (4), (5) and (6) respectively.

Figure 4. Testing the 1st Case.
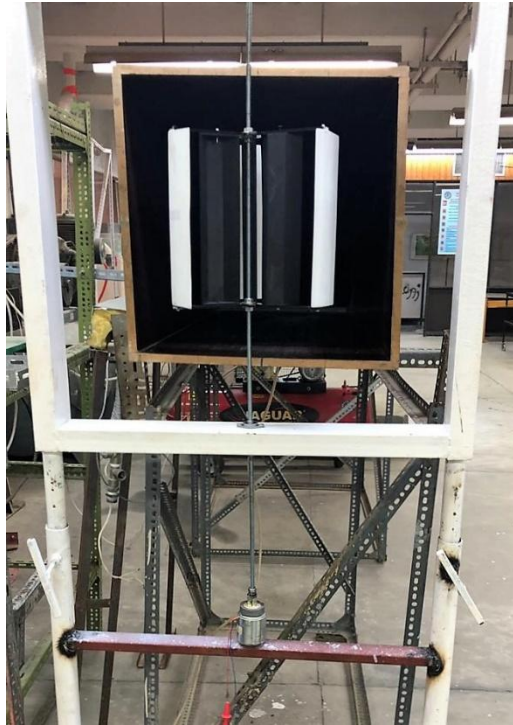

Figure 5. Testing the 2st Case.

Figure 6. Testing the 3st Case.

6. NUMERICAL SIMULATION:

Numerical Simulation was done by using Ansys / Fluent 2018 and the computational domain was designed as a rectangle domain with sizes of (1000 x 800 x 600) mm and it had been used for all computational cases. The tetrahedral mesh had been selected for the entire computational domain in ANSYS meshing tool and rotor zone meshed with a dynamic mesh to (moving mesh) that rotate with the same angular velocity of the turbine and (3,660,380, 5,026,370 and 6,595,038) elements for SB-VAWT, SB-VAWT with two reversed cavities and for SB-VAWT with three cavities had been obtained respectively and four refinement processes have been done until reach an orthogonal quality value equal to (0.7945, 0.7933 and 0.7936) for SB-VAWT, SB-VAWT with two reversed cavities and for SB-VAWT with three cavities respectively which is within very good mesh range. The skewness was equal to (0.2042, 2053 and 0.2050) for SB-VAWT, SB-VAWT with two reversed cavities and for SB-VAWT with three cavities respectively which is within very good mesh range. And for the turbulence model, SST k- ω model had been chosen to use as its neglect the main disadvantages of Standard K- ω and K- ε. And for the run time that occurs as the solver was either using the cores of the CPU in Series or Parallel, for the first case (SB-VAWT) The run time for solution reach 64 hours with a data size of 273 GB and it was in parallel solver, for the second case (2Cs-SB-VAWT) The run time for solution reach 84 hours with a data size of 77 GB and it was in series serial solver with one processor work between cores periodically. And for the third case (3Cs-SB-VAWT) The run time for solution reach 60 hours with a data size of 608 GB as it was in parallel.

7. RESULTS AND DISCUSSION:
7.1 Experimental Results:

It was observed that for wind speed versus rotational speed, that that at 4.5 m/s the maximum rotational speed occurs at the third case of Darrieus with two opposite cavities which it was 150 RPM and it followed by the second case of Darrieus with three cavities which it was 115.5 RPM and the lowest was at conventional H-Darrieus which it was 87 RPM. As shown in Figure (4).
While at 8 m/s Darrieus with two opposite cavities showed the highest rotational speed which it was 630.5 RPM while conventional Darrieus showed slightly lower rotational speed than Darrieus with two opposite cavities and it was 612 RPM and Darrieus with three cavities showed the lowest wind speed and it was 398 RPM. As shown in Fig. (7)
Finally at 10 m/s wind speed which it had been considered as a reference speed, conventional H-Darrieus showed the highest rotational speed which it was 710 RPM while Darrieus with two opposite cavities showed the second highest rotational speed and it was 690 RPM while Darrieus with three cavities showed the lowest rotational speed and it was 550 RPM and that leads to conclude that at low wind speed, conventional H-Darrieus showed a low rotational speed according to its low starting torque while at high wind speed the rotational speed was the highest corresponding to the other cases as its dynamic torque is higher. As shown in Fig. (4)
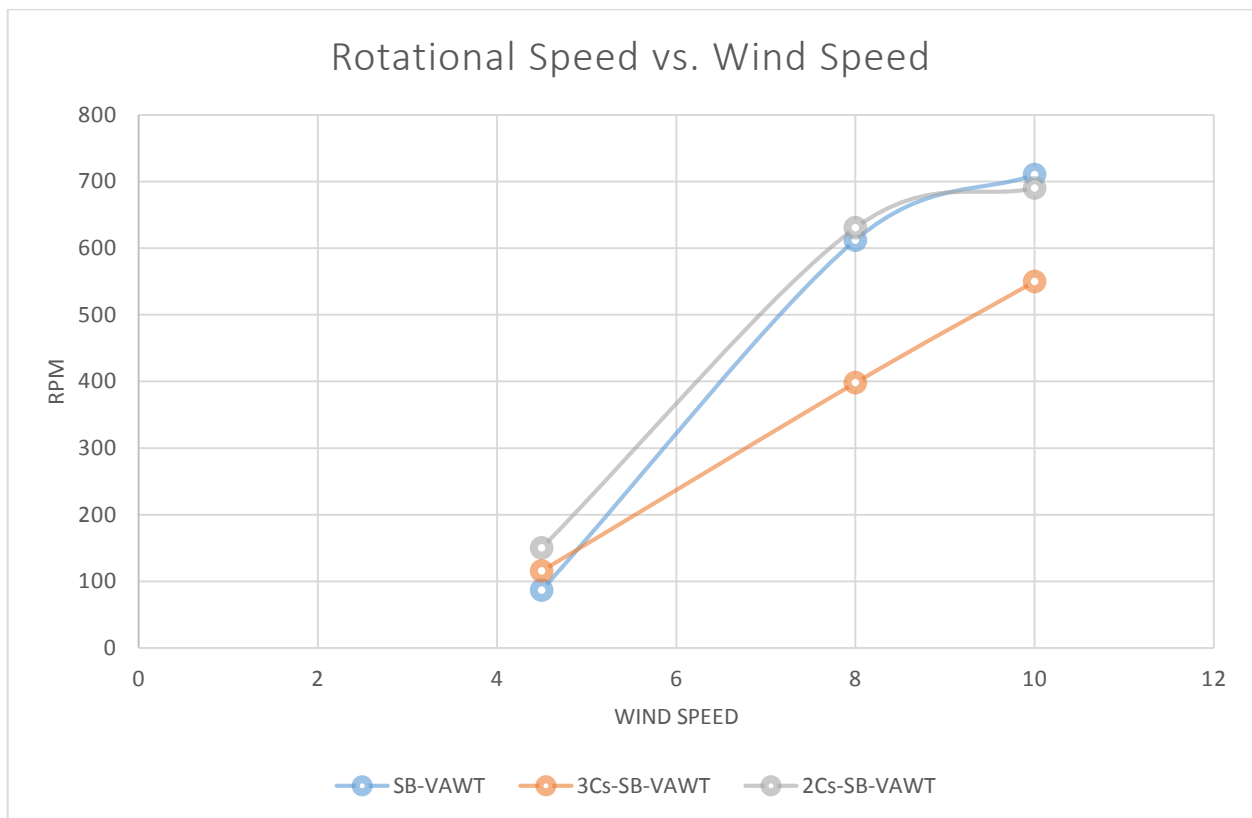

Figure 7. Rotational Speed vs. Wind Speed of the Three Turbines.

For the power coefficient, the results showed that at low wind speed (4.5 m/s) the power coefficient of conventional H-Darrieus was close to the Darrieus with three cavities although the later showed a higher performance than the first and they were 0.0487 and 0.0516 respectively.

While Darrieus with two opposite cavities showed a higher power coefficient and it was equal to 0.0602 and when the speed gets higher to 8 m/s the power coefficient of conventional H-Darrieus raised to 0.0612 while the power coefficient of Darrieus with three cavities raised much less and it became 0.05612 and the power coefficient of Darrieus with two opposite cavities became 0.0867 and when the wind speed turned to 10 m/s which it had been considered as a reference point, the power coefficient of conventional H-Darrieus raised to become 0.0705 and Darrieus with three cavities reached 0.06113 and 0.0914 for Darrieus with two opposite cavities. And it can be concluded from the figures that the power coefficient increase with increasing the wind speed and Darrieus with two opposite cavities showed the highest power coefficient with this wind speed period while Darrieus with three cavities showed the lowest power among other cases when the wind raised from low to moderate and the conventional H-Darrieus showed a similar power coefficient to Darrieus with three cavities at low wind speed and it became higher at moderate and high wind speed but still lower than Darrieus with two opposite cavities as shown in Figure (8).
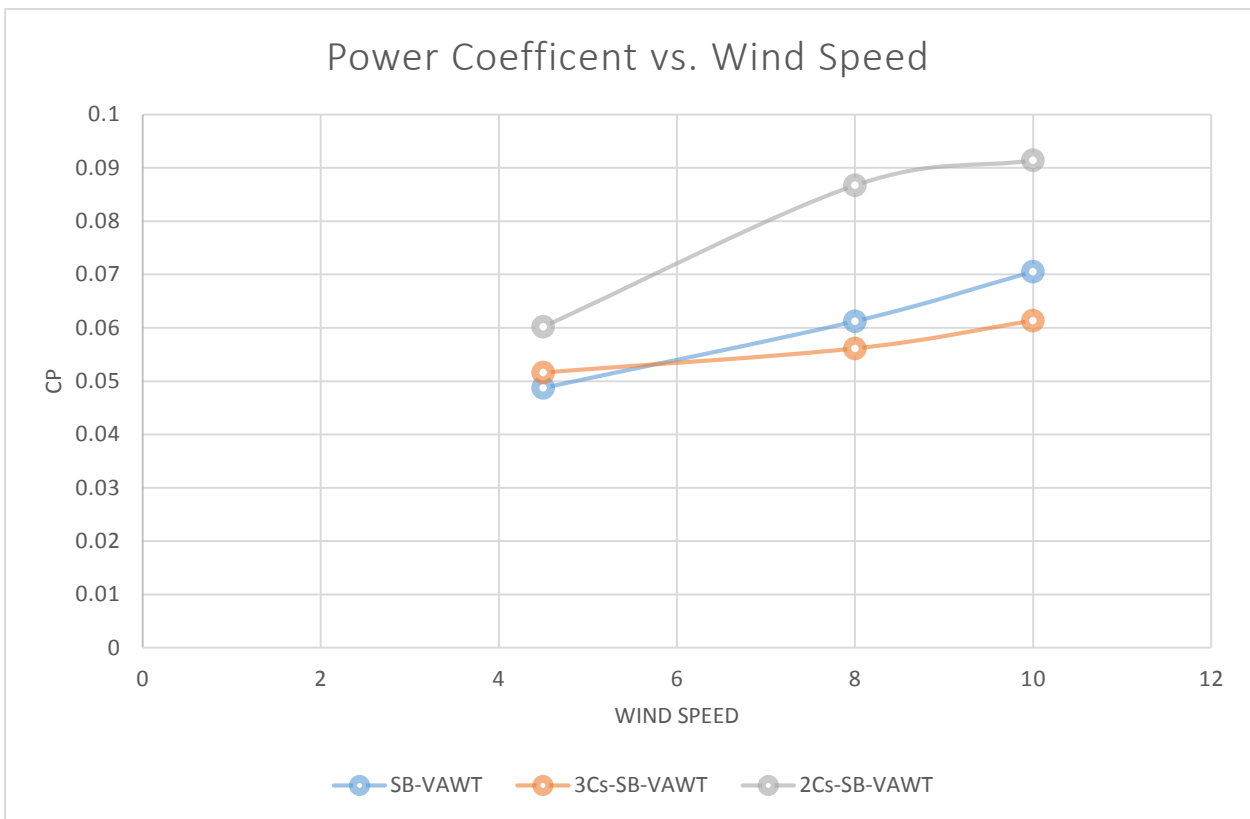

Figure 8. Power Coefficient vs. wind Speed of the Three Turbines.

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7.2 Numerical Results:

For rotational speed and angular velocity versus time and wind velocity conventional H-Darrieus run from Zero rpm to 639 rpm at the last second and the maximum rotational speed occurred at t=22 sec. and it was 665 rpm and for the angular velocity the maximum value occurred at the 7th second and it was 69.859 rad/s. and the average rotational speed for the whole run time was 608.774 rpm. Figure (9)

For Darrieus with three cavities, we can see from the figure that the rotational speed started from Zero at t=0 sec. and reached a maximum value at t=12 sec. and at the same time, the maximum angular velocity occurred and its values were 601.94 rpm and 0.787 rad/sec. respectively but the region of rotation was full of negative and positive values because of the high negative torque that predicted by the solver and we can see after t=17 sec. the stall had occurred and the rotational speed dropped down to zero while for Darrieus with two opposite cavities, the rotational speed took the same behavior of conventional H-Darrieus turbine and increased from Zero to 691 rpm at the last second and the maximum value had been recorded at t=23 sec. and it was 707 rpm and the maximum angular velocity also occurred at t=23 sec. and it was 74.116 rad/sec. and the average rotational speed for the whole run time was 612.788 rpm as seen in Figure (10) and (11).
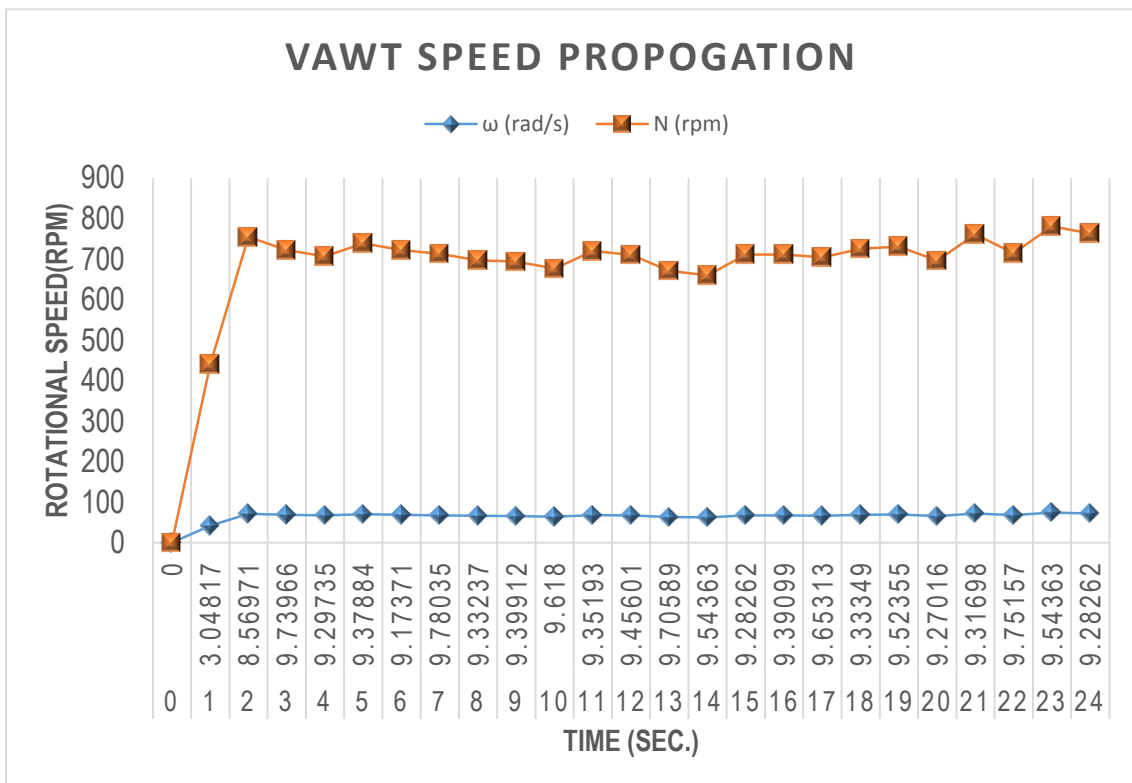

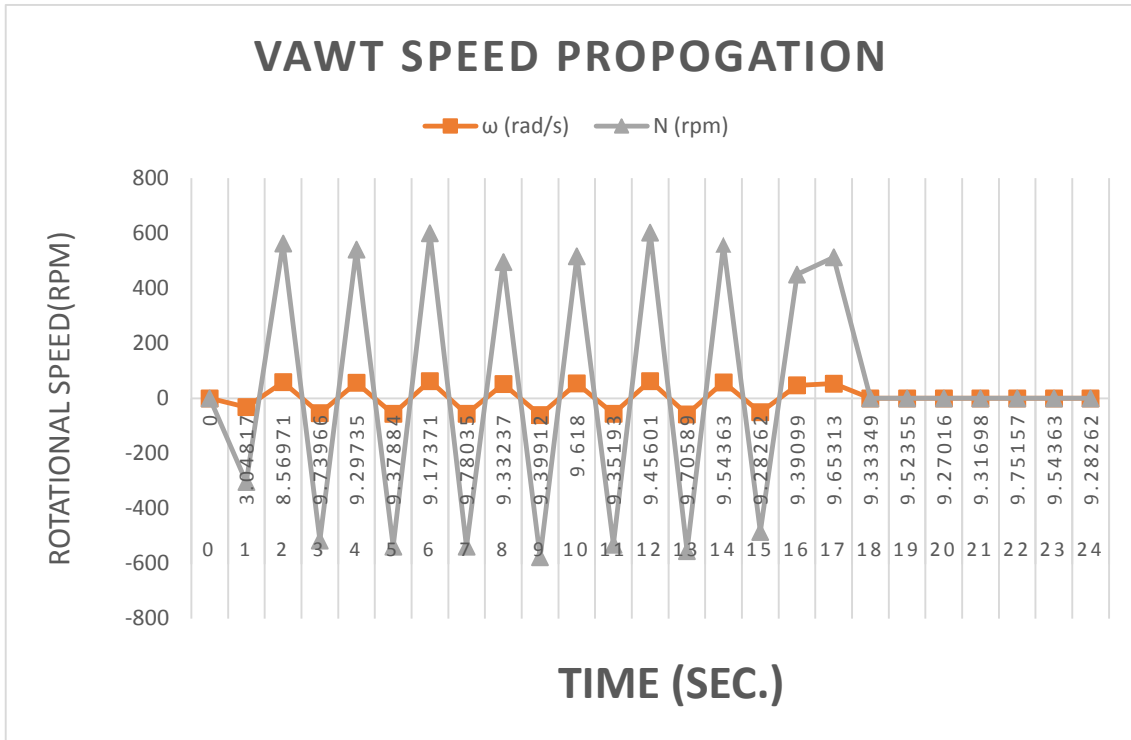**Figure 9.** N & ω versus t & V for SB-VAWT.

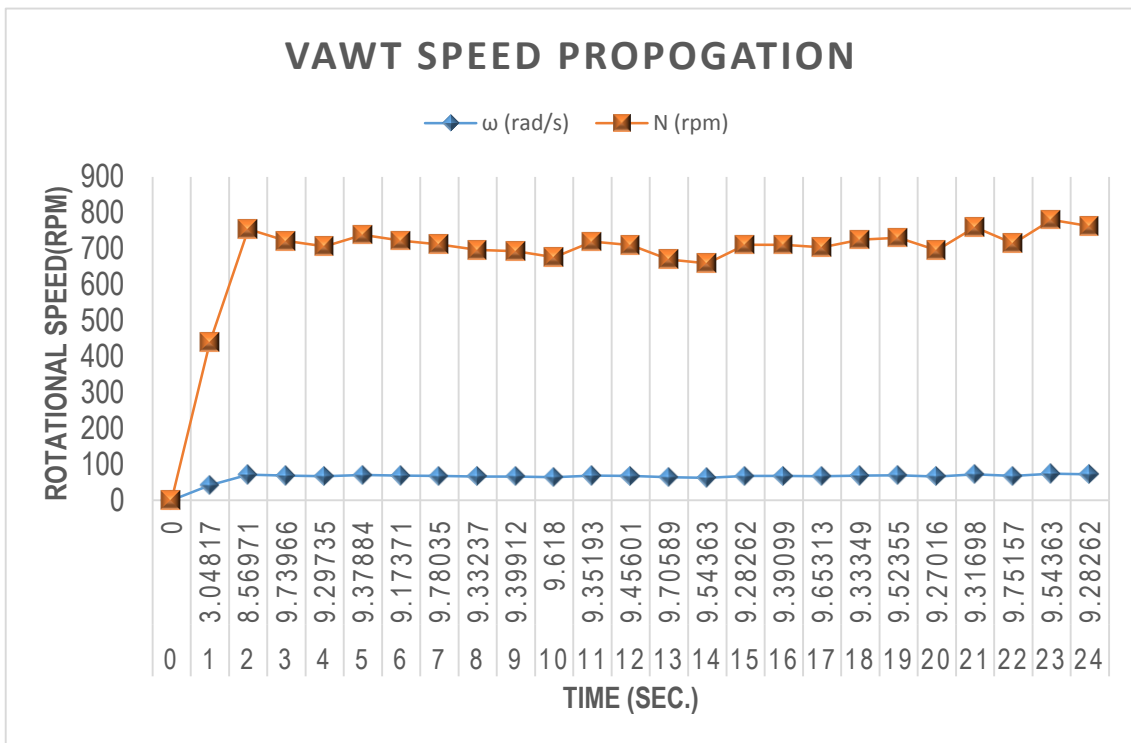**Figure 10.** N & ω versus t & V for 3Cs-SB-VAWT.

Figure 11. N & ω versus t & V for 2Cs-SB-VAWT.

And for the power coefficient as its function of extracted power which depends on the torque mainly and the angular speed to the power available in the wind as stated in the equation below:

$$Cp = (T \times \omega)/(0.5 \times \rho \times A/V\text{^}3) \tag{3}$$

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It can be concluded from the graphs that Darrieus with two opposite cavities showed the highest power coefficient with average CP=0.0404 for the rotation period and the maximum CP was equal to 0.1731 that lied in t=8 sec. followed by conventional H-Darrieus with average power coefficient of 0.0192 for the whole rotation period and reached a maximum value of 0.0680 at t=30 sec. while Darrieus with three opposite cavities showed the lowest power coefficient with an average CP of 0.0386 for the rotation period and the maximum CP was 0.235 at t=15 sec. and then decrease and turned out to be a stall as seen in Figures (12), (13) and (14).
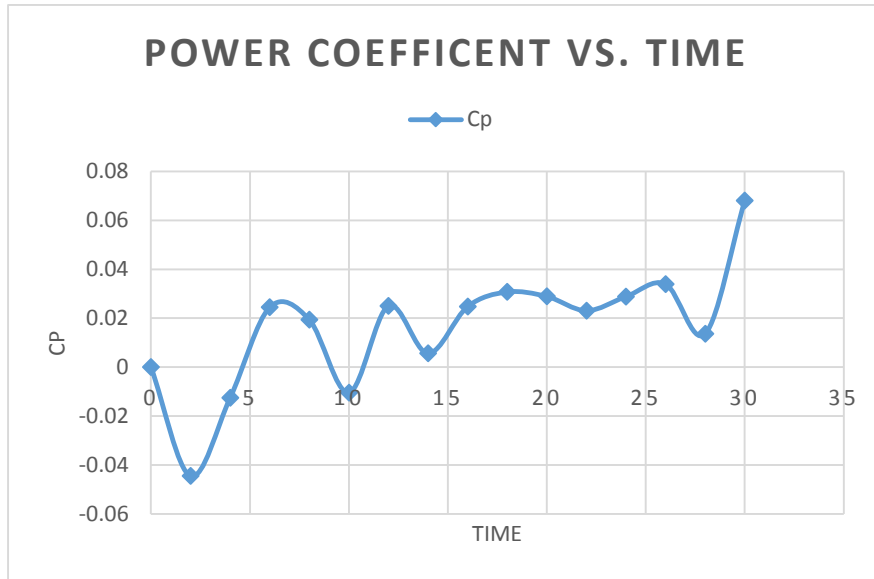

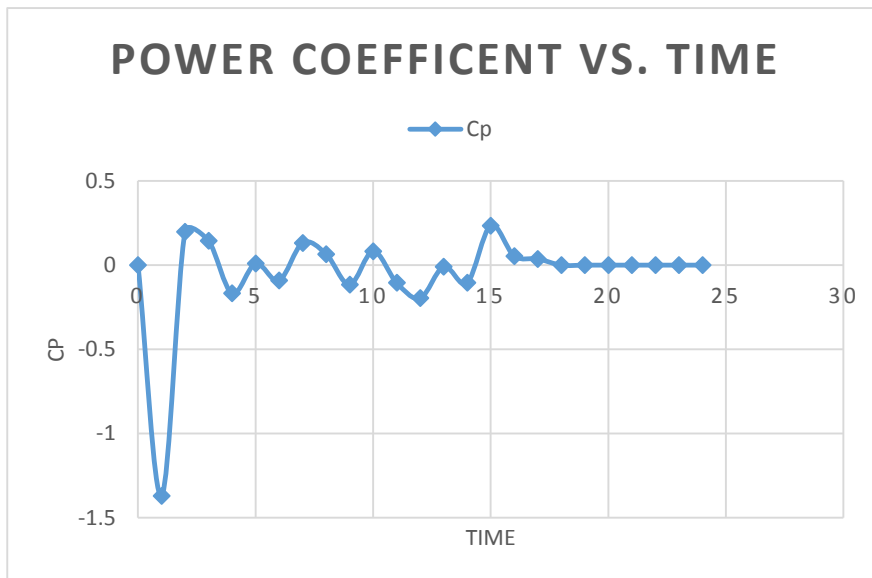**Figure 12.** Power Coefficient & versus Time SB-VAWT.

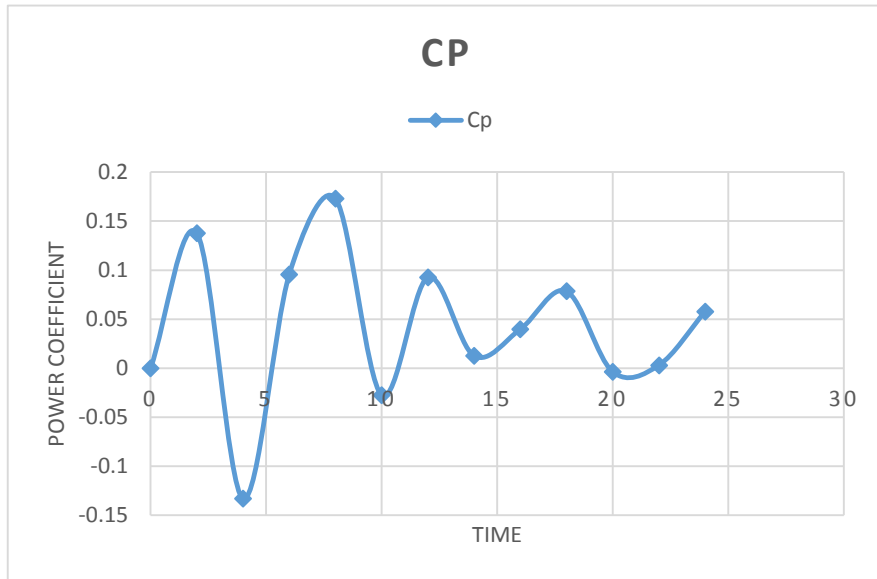**Figure 13.** Power Coefficient & versus Time 3Cs-SB-VAWT.

Figure 14. Power Coefficient & versus Time 2Cs-SB-VAWT.

For the velocity contours, Fig. (15) And (16) represent the axial and absolute velocity contours of the SB-VAWT and it showed a clear and visible recirculation zone at the trailing edge. That leads to decrease lift to drag ratio and subsequently loss of energy.
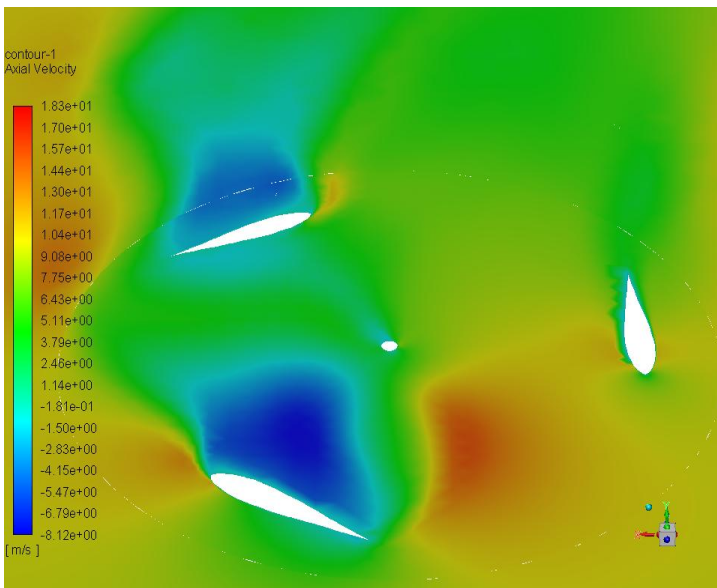

Figure 15. Axial Velocity Contour of SB-VAWT.
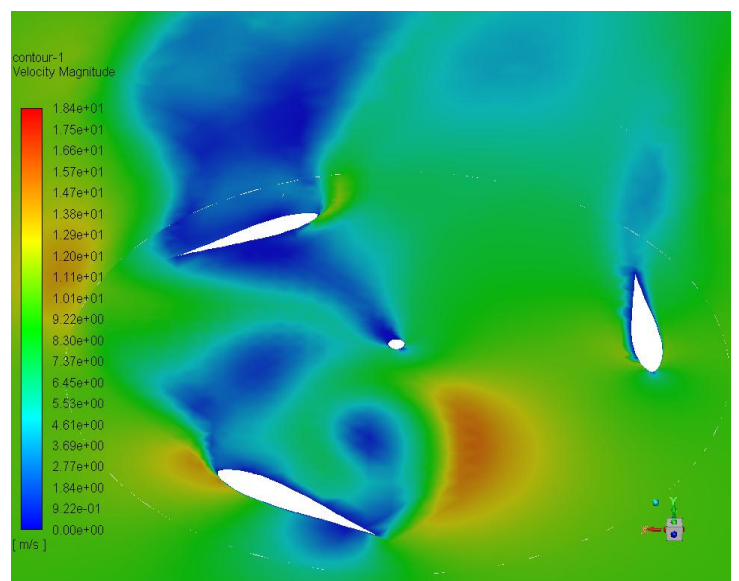

Figure 16. Absolute Velocity Contour of SB-VAWT.

On the other hand, fig. (17) And (18) represent the axial and absolute velocity contours of Darrieus turbine when adding three cavities and it showed clear and visible recirculation zone that is larger than the previous case at the cavitation side which leads to loss of energy.

At the time (t = 17 sec.) the rotor with the three cavities runs so fast and because of its high solidity it had been considered as blocked disk by the wind and the wind flows around it, so there was no mass transport through the rotor, that is no possibilities to extract energy from a moving mass so the stall occurred at this time. However, the generated tip vortices highly reduce the aerodynamic performance.

Also in this work, as the time step increased, the vortices in the core zone extend more and more, involving the upcoming blade. This phenomenon is more clear and effective when adding three cavities to the geometry, where vortices accumulate mainly in the cavitation side (turbine core) and behind the turbine. This effect reduces angular velocity for rotor domain with an increase of vorticity in the stator domain.
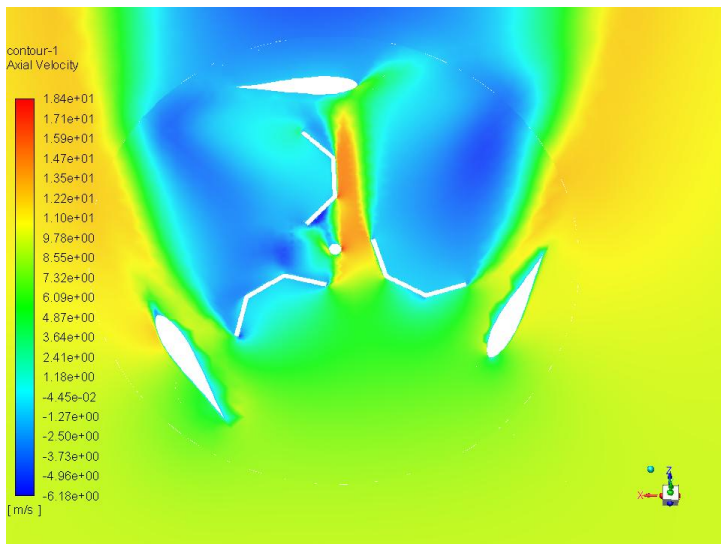

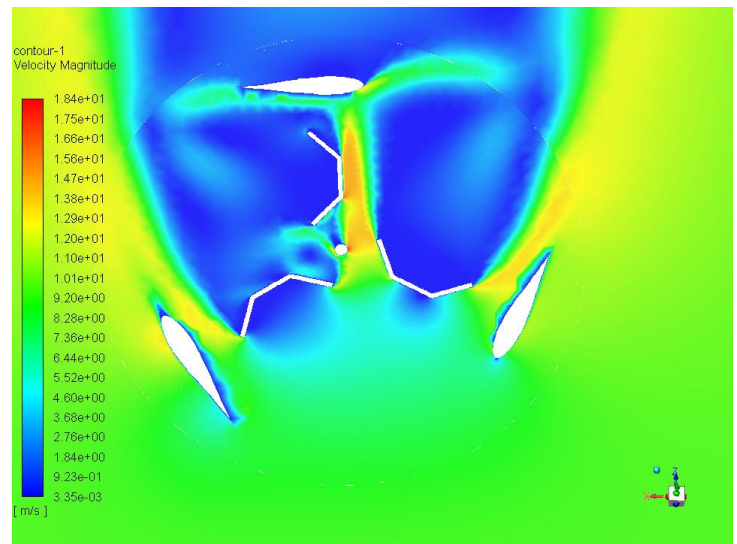**Figure 17.** Axial Velocity Contour of 3Cs-SB-VAWT

Figure 18. Absolute Velocity Contour of 3Cs-SB-VAWT

Finally, **Fig.** (19) and (20) represent the absolute velocity contours around the turbine airfoil, the axial velocity contour of Darrieus turbine when adding two opposite cavities and it showed a clear and visible recirculation zone at the cavitation side which leads to loss of energy. In this case, as the time step increased, vortex core regions extend until reach constant characteristics at time-step 1.4 sec.

From **Fig.** (17) We can see that, although the velocity zone in the downstream is much larger than the upstream of the air flow, the wake velocity is smaller than the velocity in the upstream and that occurred because of the gradient between the downstream airflow velocity and the downstream wake velocity.
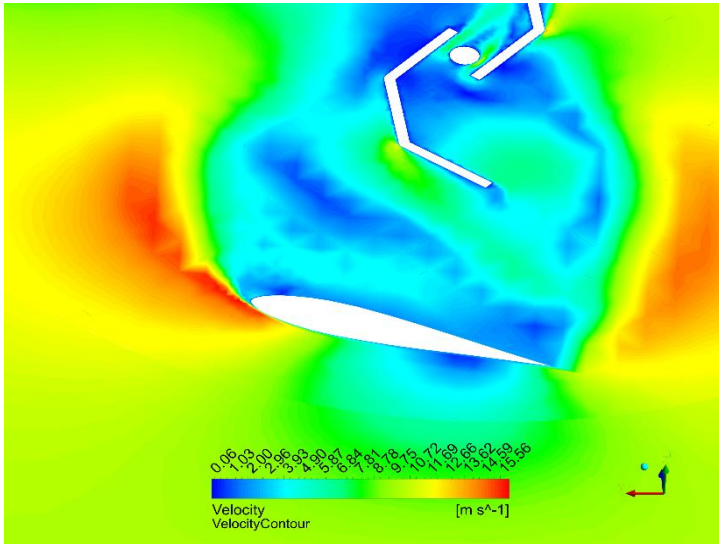
Figure 19. Absolute Velocity Contours
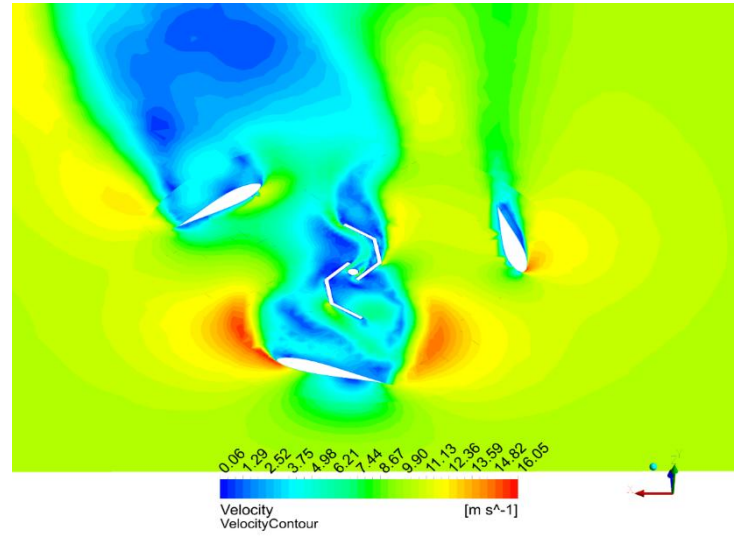Around the Airfoil of 2CSB-VAWT.

Figure 20. Absolute Velocity Contour of 3Cs-SB-VAWT.

8. CONCLUSION:

It was concluded that:

1. The cavity the was added in the turbine core in the two forms gave positive effect in the static torque (starting torque) at low wind speed (4.5 m/s) of the conventional H-Darrieus Turbine through the increment of solidity. From the Experimental results, the maximum rotational speed occurred in the third case (Darrieus with two opposite cavities) and it was 150 RPM, also it increased the dynamic torque (rotational torque) and the maximum power coefficient also occurred at the third case for low wind speed and it was 0.0602.

2. Cavities at moderate wind speed gave a slightly increment in the rotational velocity and the power coefficient for the second case but higher for the third case where the maximum result occurred and they were 630.5 RPM and 0.0867 respectively.

3. Conventional Darrieus at high wind speed (10 m/s) showed a high performance in comparison of its performance at low wind speed, when Darrieus with three cavities showed the lowest, but Darrieus with two opposite cavities showed the highest performance same as at the previous wind speeds and the rotational velocity and power coefficient were 690 and 0.0914 respectively.

4. The numerical results showed a good agreement with the experimental results although it under predicts the performance and the maximum performance also occurred at the third case and the maximum power coefficient was observed to be 0.0845 at the last time step.

5. The numerical results showed an occurring stall in the second case while the maximum performance in the third case, which leads to conclude that the cavities increased the performance until the limit of solidity and arrangement.

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Nomenclatures:

Latin Symbols:

A=Swept Area (D×H) (m^2)

A.R=Aspect Ratio (H/D) (Dimensionless)

B.R= Blockage Ratio (Dimensionless)

C=Chord Length (m)

CP= Power Coefficient (Dimensionless)

CT= Torque Coefficient   (Dimensionless)

D= Diameter (m)

HAWT= Horizontal Axis Wind Turbine

L= Length (m)

N= Number of Blades (Dimensionless)

P= Power (Watt)

R= Radius (m)

RPM= Revolution per Minute

SB-VAWT = Straight Bladed Vertical Axis Wind Turbine

T= Torque (N.m)

t= Time (s)

V= Wind Velocity (m^2/s)

VAWT= Vertical Axis Wind Turbine

2Cs-SB-VAWT= Two Cavities Straight Bladed Vertical Axis Wind Turbine

3Cs-SB-VAWT= Three Cavities Straight Bladed Vertical Axis Wind Turbine

Greek Symbols:

ρ= Density of air (kg/m³)

λ = Tip Speed Ratio (Dimensionless)

σ = Solidity (Dimensionless)