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RESEARCH ARTICLE

PERFORMANCE ANALYSIS OF S-SHAPED HELICAL HORIZONTAL AXIS WIND TURBINE "SHAWT"

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and Double Blade.

ABSTRACT

This paper presents experimental and CFD investigations for the performance of a specially designed S-Shaped Helical Horizontal Axis Wind Turbine (SHAWT). The study was carried out for single blade (two buckets)& double blades (four buckets) turbines with three different twist angles; namely (90, 120 & 180 degrees). The turbines were fabricated from wood with 0.6m diameter, 0.7mlength and 2cm thickness. Experiments were performed using 0.64m^2 wind tunnel cross section area at a constant wind speed of 8.5 m/sec. Experiments were performed to figure out the turbine performance for the several considered designs. Computational fluid dynamics model (CFD) was developed for the single blade 90 degree twist angle turbine to study the velocity and pressure contours. This aims at comparing the results with the obtained experimentally ones for the verification of the selected model. Several results were obtained for the selected designs. It was found that, within the tested range, the double blade turbine having a twisted angle of 120 degrees had the highest performance compared with the other configurations. The obtained Power Coefficient (Cp) was 0.12 at Tip Speed Ratio (TSR) of 0.52. All of the obtained results were compared with other investigators and a fair agreement was found.

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INTRODUCTION

There are lots of energy sources round the whole world that can be used in energy generation in the market. Due to global warming and the lake of petroleum products, the need for a new way for energy generation becomes so clear. There is a real need to keep the earth green and to search for a new alternative source of energy. So, renewable energy sources were found to be one of the most suitable ways to solve this problem. Scientists and engineers across the globe start to battle to achieve a way to supply it with high power and efficiency with good investment. Wind energy is one of the most important renewable sources of energy round the world which is clean source of energy. The HAWT works at high wind speed, with high power coefficient. It must be directed to the wind direction. The VAWT works at low wind speed, and low power coefficient. It works when wind comes from all directions(Islama *et al*., 2013; Hamdann *et al*., 2014). The VAWT has various configurations, the main designs are Savonius and Darrieus wind turbines of different shapes (Hamdann *et al*., 2014; Jonny Hylander *et al*., 2010). Savonius wind turbine is a vertical axis wind turbine and considered to be drag turbine. Savonius wind turbine is an S-Shaped cross section constructed by two semi-circle buckets (Jonny Hylander *et al*., 2010). This turbine is divided into 2 bucket blades, 3 bucket blades, single, double or triple stages and helical Savonius with variable parameters and different performance. D'Alessandro *et al*. (2010) presenteda Savoniusturbine with 2 buckets of 0.4m diameter subjected to wind speed range of 6 to 12 m/sec with 1 m/sec step. They found that the maximum power coefficientC_p=0.26 at TSR =0.8 and torque coefficient of 0.46 at TSR= 0.18.Sukanta Roy *et al*. (2014), show Savonius wind turbine with 2 buckets of 0.23m diameter, 0.23m height subjected to wind speed of 6 m/sec. They also studied the turbine performance and found maximum power coefficient of C_p= 0.25 at TSR= 0.65 and torque coefficient is 0.51 at TSR= 0.17. BurcinDedaAltan *et al*. (2008) studied wind turbine with 2 buckets0.352m diameter0.32m height subjected to wind speed 7 m/sec and got C_p=0.16 atTSR = 0.33. Mohammed Hadi Ali (Mohammed Hadi Ali, 2013; Ian Duffett *et al*., 2009) performed comparison between 2 buckets and 3 buckets performance at low wind speed. The result of the turbine of 2 buckets shows that maximum power coefficient C_p = 0.21 at TSR= 0.8 and maximum torque coefficient 0.4 at TSR= 0.35. Moreover, the result of three buckets wind turbine shows the maximum C_p was0.16 at TSR 0.8 and the maximum C_p=0.33 at TSR= 0.35.

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This means as the number of blades increases, the drag forces increases and increases the reverse torque and this affect the performance. The helical Savoiuscombines the advantages of the Savonius turbine with the twisted design of the helical Darrieus. The blades, used for converting the power of the wind into torque on a rotating shaft, are uniquely designed to catch the wind from all directions, while the skewed leading edges reduce resistance to rotation (Ian Duffett *et al*., 2009). Damak *et al*. (2012) review helical Savonius of twist angle 180 Degrees with dimensions fit in a wind tunnel of cross section $0.4m^2$ and wind speed 8 m/sec. The results show the maximum C_p of 0.18 at TSR of 0.44 and maximum torque coefficient of 0.6 at TSR of 0.34. Kamoji *et al*. (2008) studied helical Savoniusturbine of twisted angle 90 degrees with dimensions 0.25m height and 0.25m diameter tested at a wind speed 8 m/sec. The experimental result shows that maximum C_p of 0.16 at TSR of 0.61 and the maximum torque coefficient of 0.26 at TSR of 0.62.Moreover, several variations on both curved-and straight blades configurations have been investigated. Darrieus VAWT has produced several variations, most notably Helical H-rotor. In addition, investigations into clustered Darrieus VAWT have been currently taking place, which show promising results over an HAWT wind farm (Willy Tjiu *et al*., 2014). After previewing the previous work, none of these works were performed on S-Shaped Helical Horizontal Axis Wind Turbine. This paper presents a continuation of the work including experimental and CFD investigation of S-Shaped Helical Horizontal Axis Wind Turbine at different helical twist angles of 90,120 and 180 degrees with different number of blades (Buckets) Single blade (Two Buckets) and Double blade (Four Buckets).

Experimental setup and procedures

In the experimental setup, **Figure (1)** shows the shape of the blades during manufacturing and the obeyed steps in the manufacturing for the turbine blades. It shows that the blades were made from strips of wood joined together to form the S-Shaped turbine and to be twisted to the desired angles as can be seen. Awind tunnel was utilized having a cross section area $0.64m^2$. It is used to provide a constant wind speed of 8.5 m/sec through a 5.36 HP blower. The tunnel was used to test the S-Shaped Helical Horizontal Axis Wind Turbine (SHAWT). Experimental investigation was used to study the performance of six turbines, S-Shaped Helical Horizontal Axis Wind Turbine (SHAWT) model of dimensions 0.6m diameter and 0.7m height at three helical shapes of twist angles 90, 120 and 180 degrees. The two and four blade twist angles were measured from the upper segment to the lower segment. The torque was measured from no load to maximum load using a rope wrapped around the pulley and tied to a spring gauge of accuracy ± 2%, and the rotational speed was measured for each torque using tachometer of resolution 1 rpm. **Figure (2)** shows the assembly of the S-Shaped Helical Horizontal Axis Wind Turbine with the connecting joints, the shaft mounted on the bearings. **Figure (3)** shows the wind turbine at the exit section of the tunnel. The figure also shows the pulley fixed on the same axis of the wind turbine to measure the torque. The wind velocity was measured by a calibrated anemometer with accuracy ±3%. The turbine was running; first of all; at no load to measure the maximum speed by the digital tachometer. Applying the braking load was utilized by using a rope wrapped around the pulley.

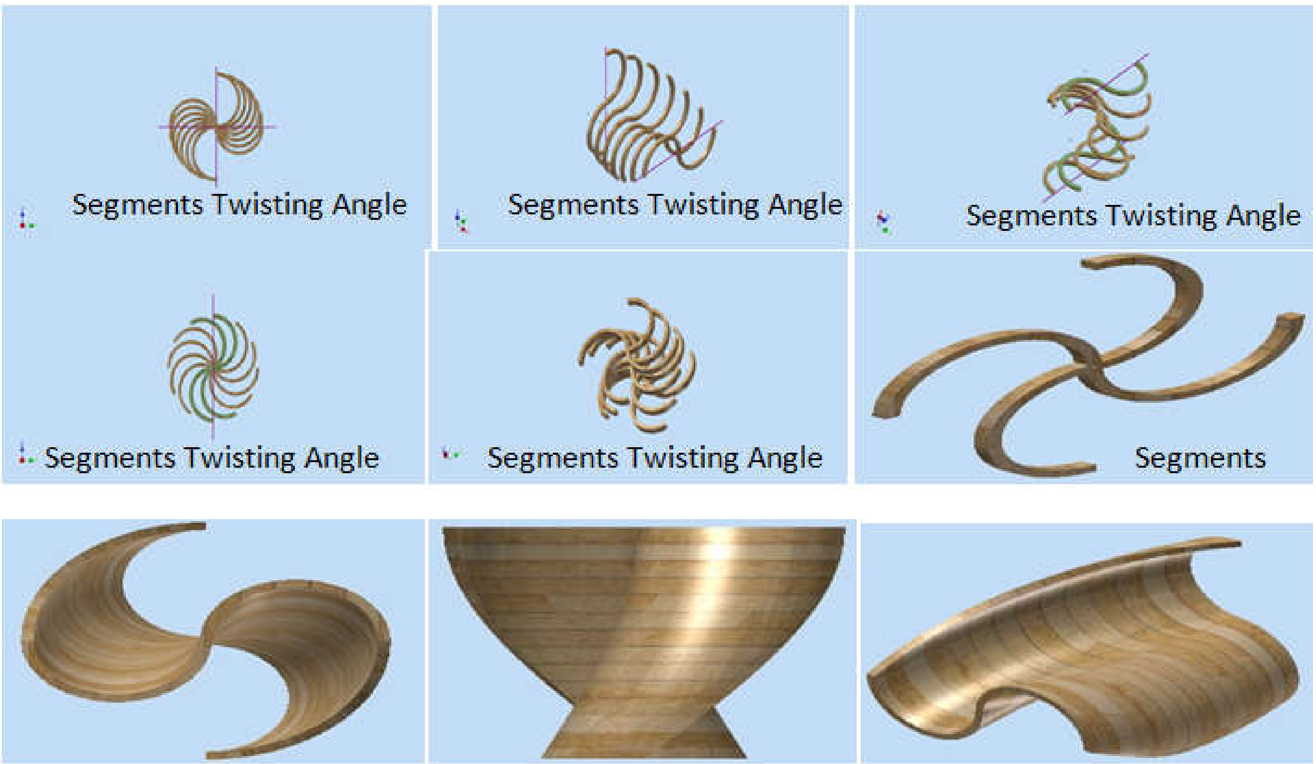

Figure 1. Manufacturing steps

Then the measurement of braking torque was taken by measuring the difference between the tension forces in the two sides of the rope. **Figures(4 from a to f)** show the different configurations of the used S-Shaped Helical Horizontal Axis Wind Turbine.

Calculation

Tension (T_1) = T_1 × 9.81Tension (T_2) = T_2× 9.81Torque (τ) = (T_2 - T_1) × Angular rotational (ω = 2ΠN / 60)

Projected Area ($A_{pro.}$) = Length of the Turbine ×Diameter of the Turbine

Actual Power (P_{act}) = τ × ωAvailable Power (P_{av}) = ½ × ρ_{air}× V^3× $A_{pro.}$

Tip Speed Ratio TSR (λ) = (ω × $r_{turbine}$) / V
Power coefficient (C_P) = P_{act} /P_{av} Torque Coefficient (C_T) = C_P /λ

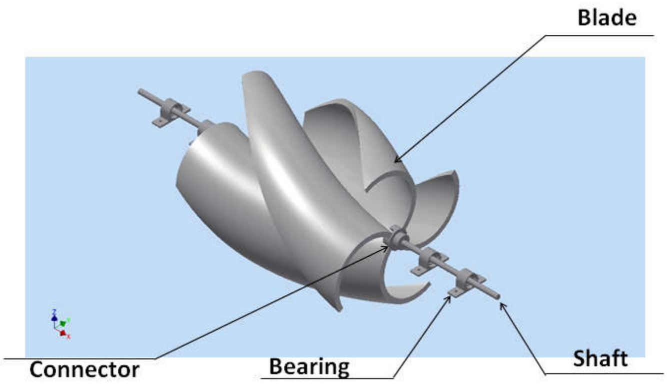

Figure 2. Assembly of the S-Shaped Helical Horizontal Axis Wind Turbine

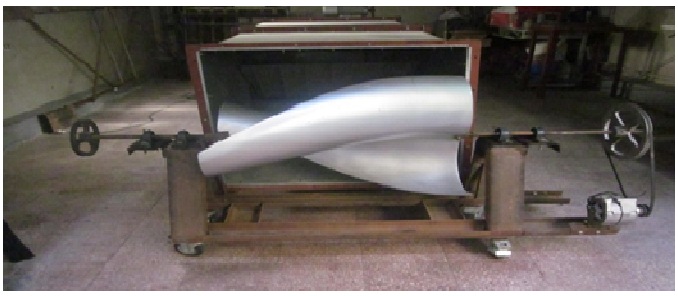

Figure 3. Test Section

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental results were analyzed and these results are represented in the power coefficient versus tip speed ratio (TRS) starting from no load to maximum load. So, we can compare the performance of different S-Shaped Helical Horizontal Axis Wind Turbine according to the change in twist angle 90, 120 and 180 degrees with different number of blades. The following are the set of the obtained results. **Figure (5), s**how that the double blade turbine, Figure (4-d), had higher C_p than that for the single blade turbine, Figure (4-a), where the double blade turbine hasmaximum power coefficient C_p of around 0.106 at Tip Speed Ratio λ =0.429 while the single blade turbine gives maximum power coefficient C_p of 0.091 at Tip Speed Ratio λ= 0.6.

Figure (6), that the double blade turbine, Figure (4-d), had higher torque coefficient than the single blade turbine, Figure (4-a)**.**After the intersection point, C_T = 0.16 and λ=0.56 the torque coefficient of single blade becomes higher the double blade.

Figure (**7**), that the double blade turbine, Figure (4-e), hasslightly higher power coefficient than the single blade turbine, Figure (4-b). The double blade turbine has maximum power coefficient C_p of 0.12 at Tip Speed Ratio (λ) of 0.52 while single blade turbine has maximum power coefficient C_p of 0.113 at Tip Speed Ratio λ of 0.6.

Figure (8), that the double blade, Figure (4-e), had higher torque coefficient than single blade, Figure (4-b).After the intersection point C_T = 0.2 and λ=0.58 the torque coefficient of single blade becomes higher the double blade.

Figure (9), that the double blade turbine, Figure (4-f), had higher power coefficient than the single blade, Figure (4-c), **T**he double blade has maximum power coefficient C_p of 0.085 at Tip Speed Ratio λ of 0.46 while single blade turbine has maximum power coefficient C_p of 0.058 at Tip Speed Ratio λ of 0.42.

Figure (10), that the double blade turbine, Figure(4-f), has higher torque coefficient than the single blade turbine, Figure (4-c).

Comparison between the different twist angles for a single blade

Figure (11): (C_p Versus λ) for single blade at different attwist angles of 90, 120 and 180 degrees. It was found that the maximum peak of power coefficient of the single blade was achieved attwistangle 120 which is C_p= 0.113 at Tip speed Ratio λ = 0.6.

Figure (12): (C_TVersus λ) for single blade at different at twist angles of 90, 120 and 180 degrees. It was found that the maximum torque coefficient obtained at twisting angle 120 degrees.

Comparison between the different twist angles for a double blades

Figure (13):(C_pVersus λ) for double blades at different twist angles of 90, 120 and 180 degrees. It was found that the maximum peak of the power coefficient achieved at double blade turbine at twist angle 120°. The power coefficient was around C_p= 0.12Tip Speed Ratio λ =0.52

Figure (14): (C_T Versus λ) for the double blade at different twist angles of 90, 120 and 180 degrees. It was found that the maximum torque coefficient at double turbine is attwist angle of120 degree, C_T= 0.399at Tip Speed Ratio λ= 0.19

Figure (a) Single blade of twist angle 90°

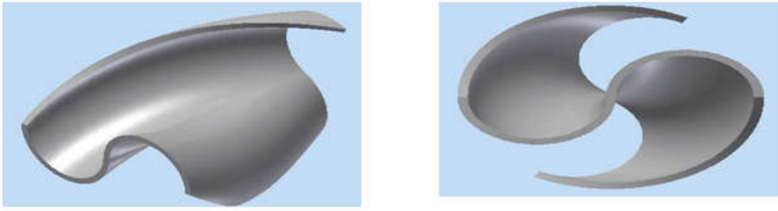

Figure (b) Single blade of twist angle 120°

Figure (c) Single blade of twist angle 180°

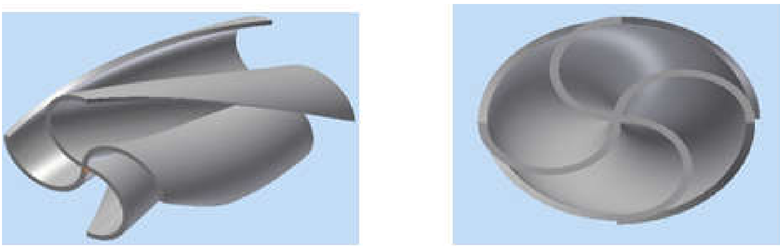

Figure (d) Double blade of twist angle 90°

Figure (e) Double blade of twist angle 120°

Figure (f) Double blade of twist angle 180°

Figure 4. (a-f) Schematic Diagram for Single and Double blade at twist angles (90°,120°,180°)

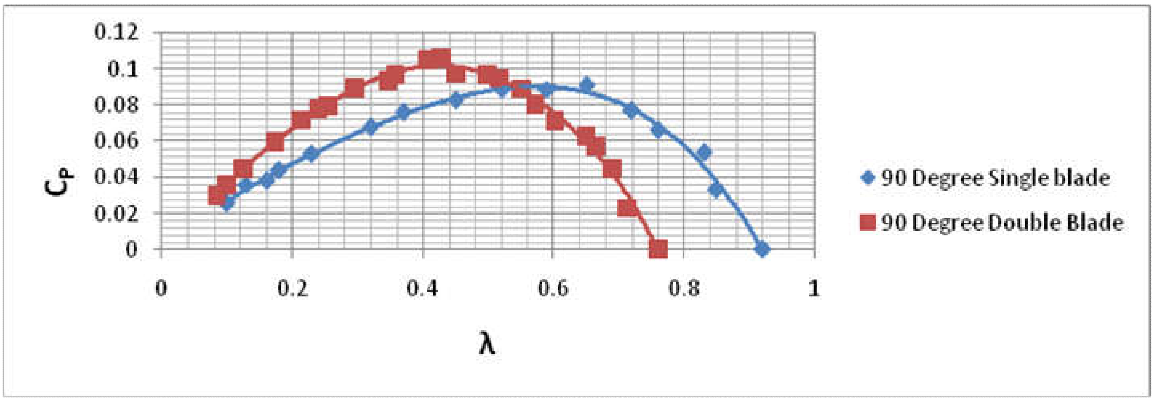

Figure 5. (C_pVersus λ) for single and double blade at twist angle 90°

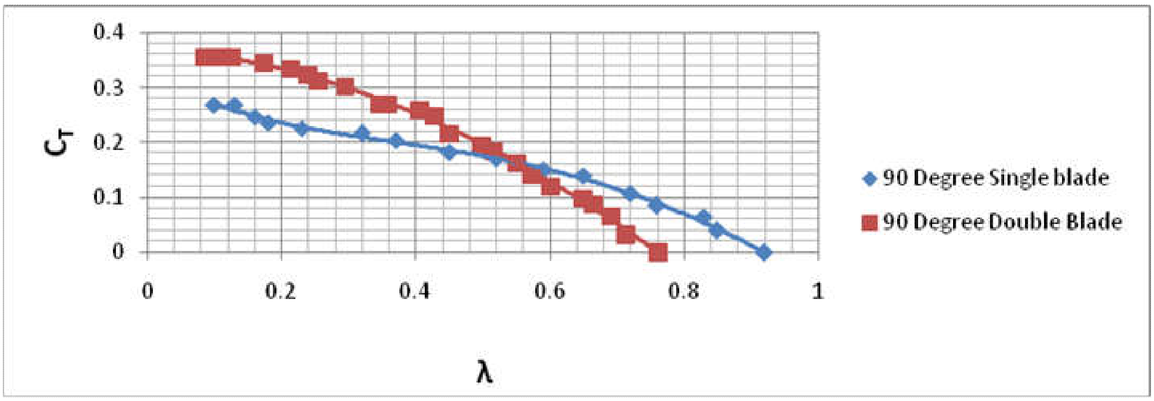

Figure 6. (C_TVersus λ) for single and double blade at twist angle90°

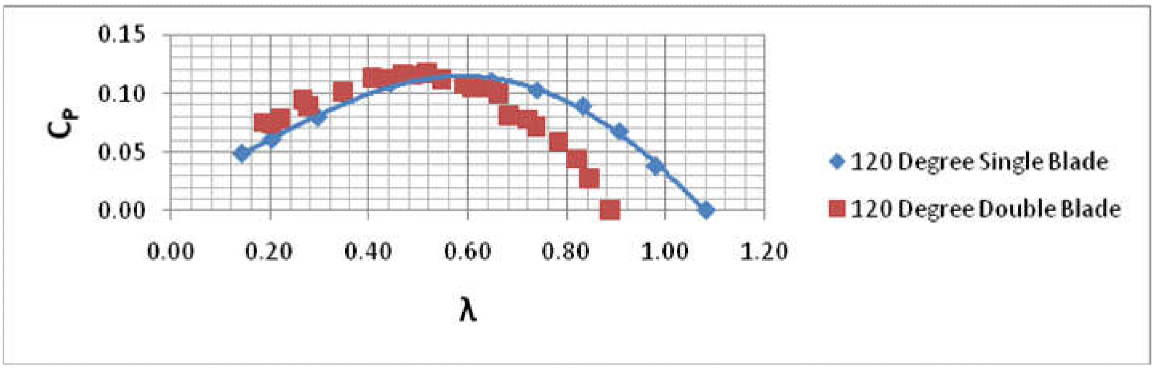

Figure 7. (C_pVersus λ) for single and double blade at twist angle 120°

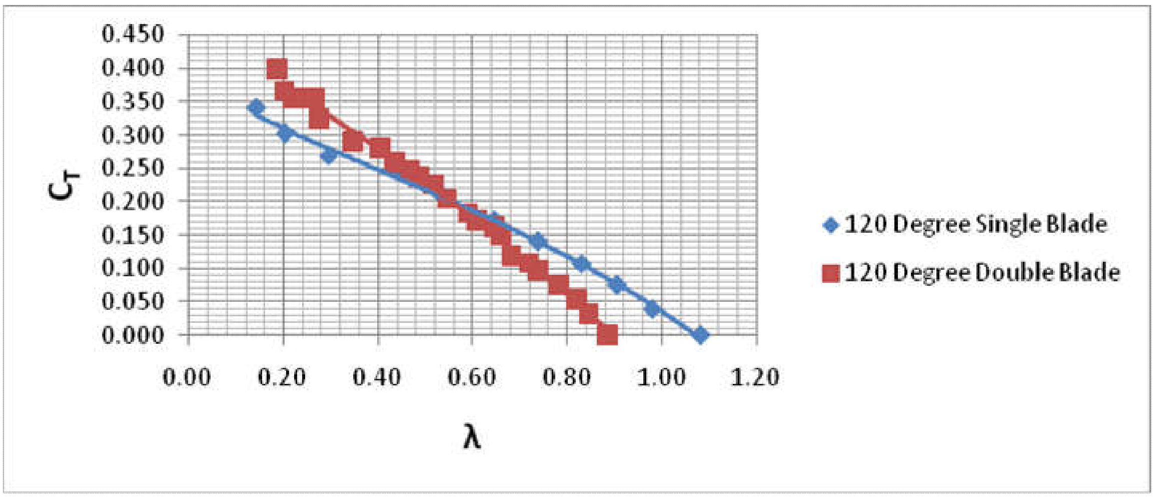

Figure 8. (C_t Versus λ) for single and double blade at twist angle 120°

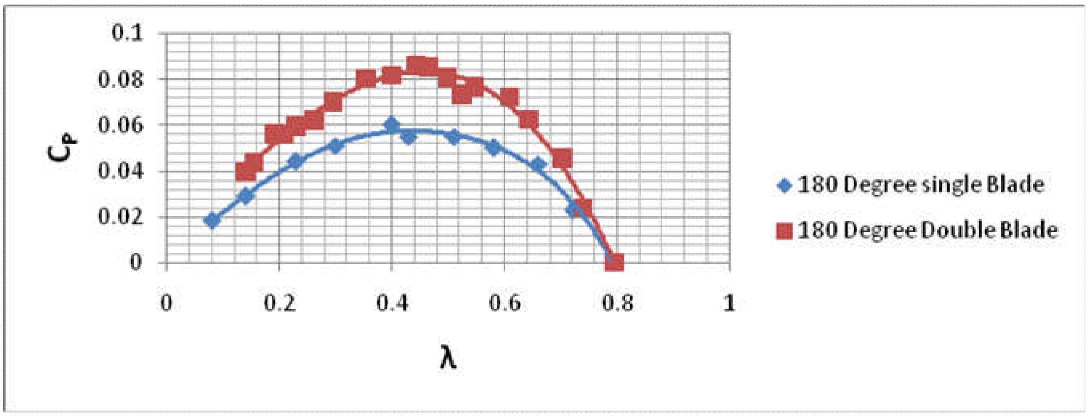

Figure 9. (C_pVersus λ) for single and doublebladeat twist angle 180°

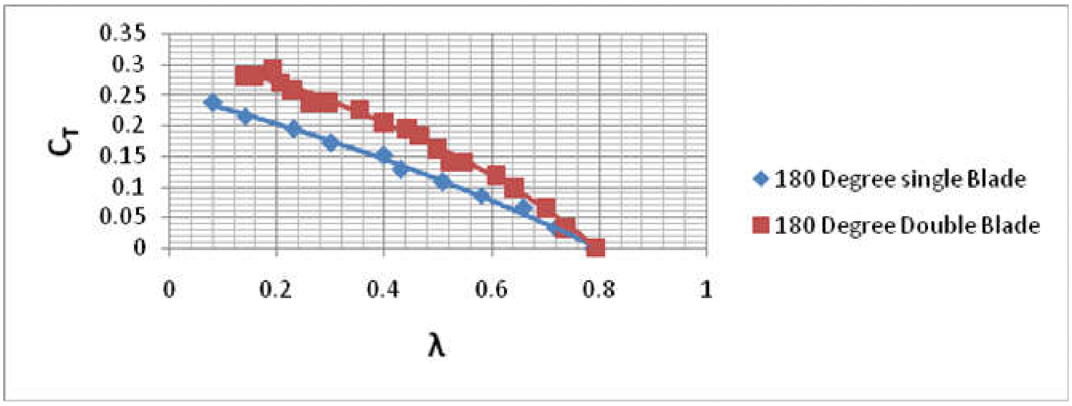

Figure 10. (C_TVersus λ) for single and double blade at twist angle 180°

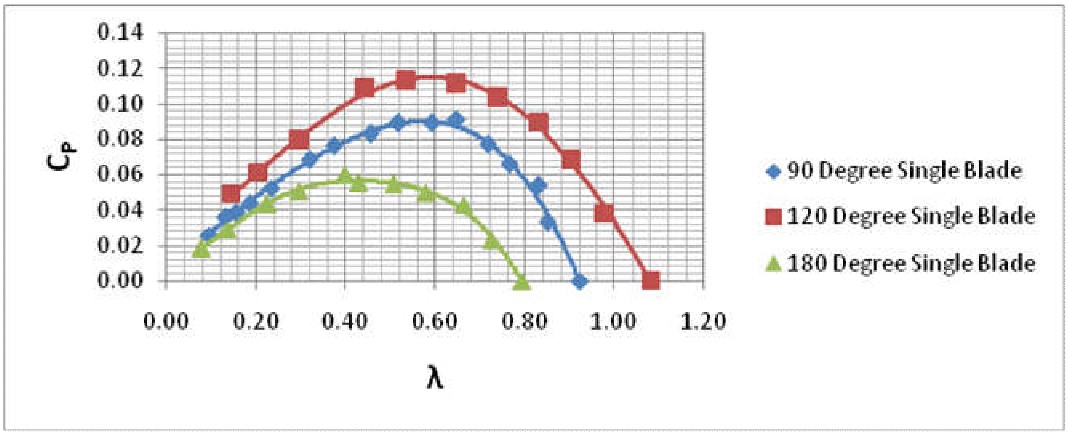

Figure 11. (C_pVersus λ) for single blade at different twist angles90°, 120° and 180°

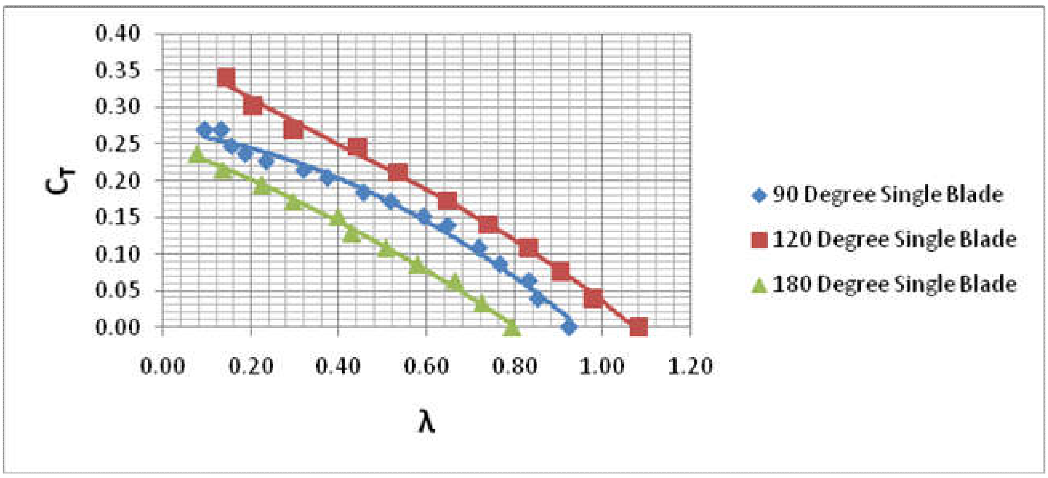

Figure 12. (C_T Versus λ) for single blade at different twist angles 90°, 120° and 180°

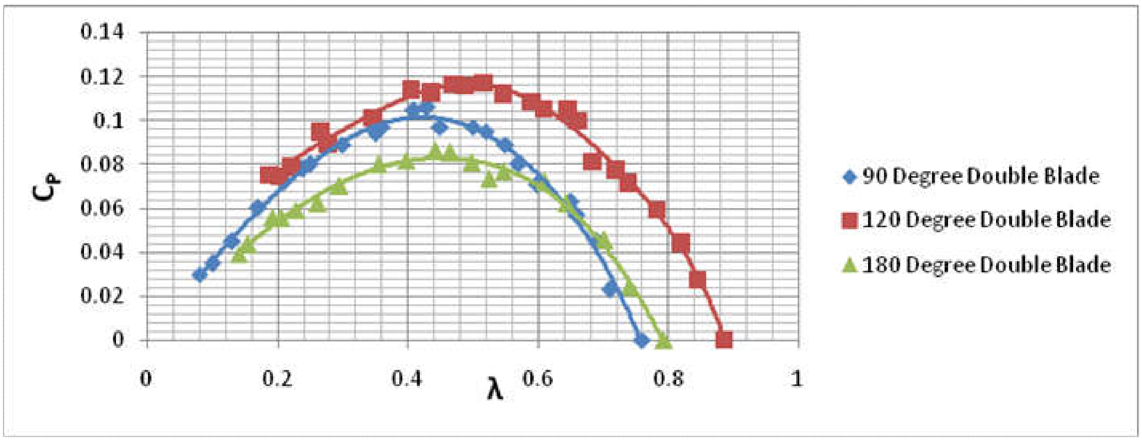

Figure 13. (C_pVersus λ) for Double blade at different twist angles 90°, 120° and 180°

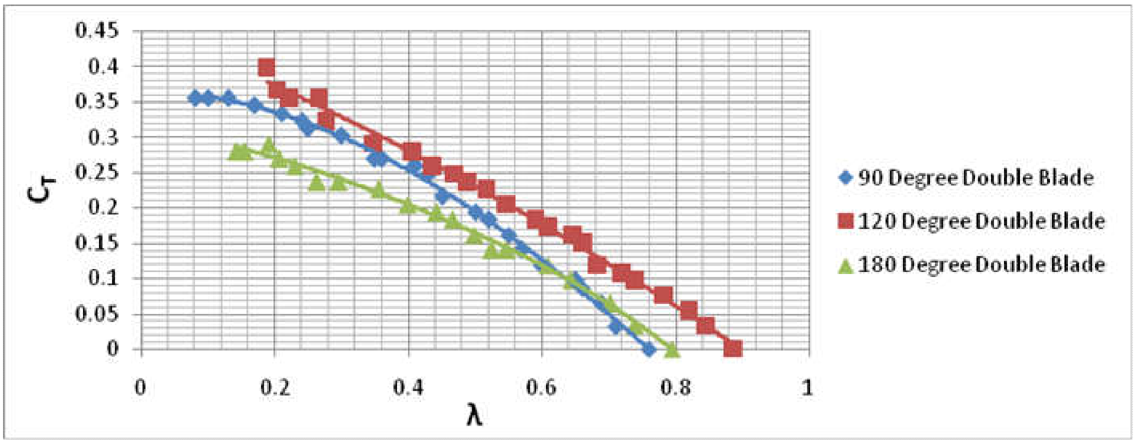

Figure 14. (C_T Versus λ) for Double blade at different twist angles 90°, 120° and 180°

Experimental investigations show the following

- The most efficient S-Shaped Helical Horizontal Axis Wind Turbine for the double blade is attwist angle of 120°at power coefficient (C_p) of around 0.12and Tip Speed Ratio (λ) 0.52.
- The most efficient S-Shaped Helical Horizontal Axis Wind Turbine for the Single blade is at twist angle of 120° at power coefficient (C_p).
- The lowest efficient S-Shaped Helical Horizontal Axis Wind Turbine for the Double blade is at helical of twist angle 180 degrees.
- The lowest efficient of the S-Shaped Helical Horizontal Axis Wind Turbine of Single blade at twist angle180 degrees.
- The maximum torque coefficient is for S-Shaped Helical Horizontal Axis Wind Turbine for the double blade is at twist angle120 degrees.
- The maximum torque coefficient is for S-Shaped Helical Horizontal Axis Wind Turbine for the Single blade is at twist angle 120 degrees.
- The minimum torque coefficient is for S-Shaped Helical Horizontal Axis Wind Turbine for the double blade is at twist angle 180 degrees.
- The minimum torque coefficient is for S-Shaped Helical Horizontal Axis Wind Turbine for the single blade is at twist angle 180 degrees.
- The double blade S-Shaped Helical Horizontal Axis Wind Turbine at different angle profile is more efficient than the Single blade S-Shaped Helical Horizontal Axis Wind Turbine.

Computational fluid dynamics of S-Shaped Helical Horizontal Axis wind turbine at twist angle 90 degrees

A.Designing

1.Rotating turbine(S-Shaped Helical wind Turbine) at twist angle90 degrees, diameter 60cm and length 70cm “Sliding-Mesh Method ”

2.Domain(12-17)

a)Main Domain

•Plan View

In the plan section, the turbine is at a distance 5D from the wind source (upstream) and after the turbine the distance is 10D (Downstream), where the air is to recover and get free from wakes.

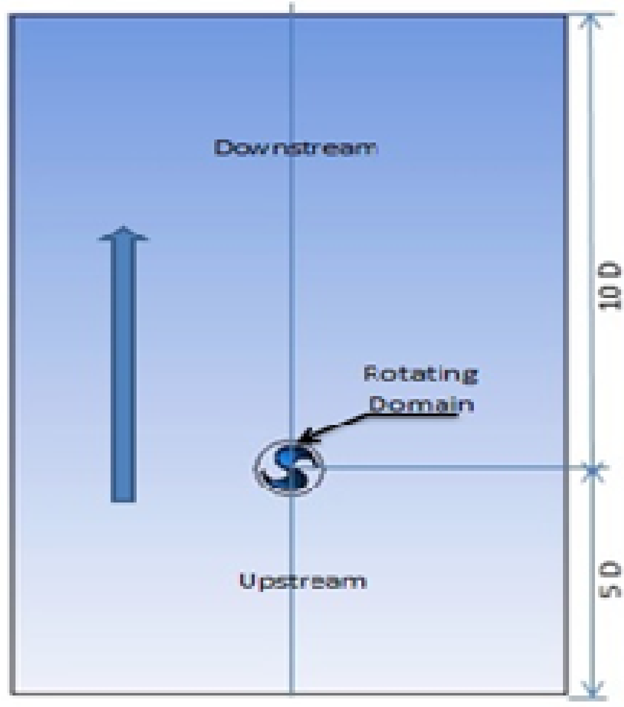

Figure 15. Main Domain SHAWT with twist Angel 90°

b)Rotating Domain "Cylinder around the turbine (Shown Figure (15))

- Diameter of the rotating domain is 1.2 times the turbine diameter
- The length of the rotating domain is 1.2 times the turbine length. The turbine is placed in a dynamic flow of fluid air and the study was performed for the flow over the S-Shaped helical wind turbine with helix angle 90 degrees

3.Meshing Figure(16)

(Meshing Dependency test "Estimate Trial" (PinkuDebnathRajat Gupta, 2013; Patel *et al.*, 2013;Can Kang *et al.*, 2013; PinkuDebnath *et al.*, 2014; AReza Hassanzadeh *et al.*, 2013; Bachu Deb *et al.*, 2013)

- Standard k-ε model was used (PinkuDebnathRajat Gupta, 2013; Patel *et al.*, 2013; Can Kang *et al.*, 2013; PinkuDebnath *et al.*, 2014;ARezaHassanzadeh *et al.*, 2013; Bachu Deb *et al.*, 2013)
- Turbulence model "Calculate the effect of turbulence in turbulent flow"
- Y+ Range 30:100 (Y+) Dimensionless number to estimate the first cell height on the turbulent blade to make the meshing and catch the boarding layers to collect the data correctly. The reason for the different scale is to obtain suitable values for the non-dimensionless wall unit y+ (between 30 and 100) for the use of wall functions, without the need to change the reference wind speed or the grid resolution for this purpose.

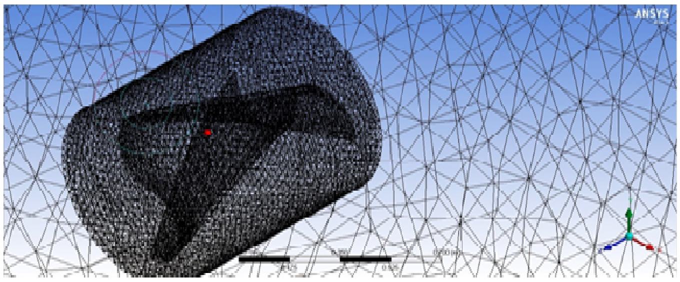

Figure 16. Meshes SHAWT at twist angles Angel 90°

B.Program Setup mode(PinkuDebnathRajat Gupta, 2013; Patel *et al.*, 2013; Can Kang *et al.*, 2013; PinkuDebnath *et al.*, 2014;ARezaHassanzadeh *et al.*, 2013; Bachu Deb *et al.*, 2013)

1. Standard K-ε model
2. Pressure base "subsonic"
3. Incompressible flow
4. Sliding mesh 3D
5. 3D Transient
6. Time step size each degree of rotation
7. Error conversion 10^{-5}
8. Fixed speed 8.5m/sec and change the rotating speed to get different tip speed ratio (λ).
9. Take number of complete rotation till reach stabilization.

C.Results

1.Velocity distribution, Figure(17),

A.The flow Up stream

The air flow from the left hand side "upstream "to the right hand side "downstream," with velocity 8.5m/sec. This represents the main air flow velocity (Orange color) that incident on the wind turbine at point where direct impact occurs between the air flow and the turbine at stagnation point, where sudden drop in velocity to 2.7m/sec (baby blue color).

B.The flow of air over the turbine

Since the turbine is S-Shape Helical wind turbine and rotates anti-clock wise, the flow of air incident the helical bucket with high velocity. As it rotates, the velocity of air inside the helix decreases due to vortex and swirling motion which lead to a decrease in velocity to 2.7m/sec (Baby blue color) and as we go outside the helix and study the flow outside the turbine at the tip, we will find the velocity increases due to the high rotational speed reaching 10.4m/sec (red color).

C.The flow of air downstream

The flow of air leaves the turbine with variable velocities leads to formation of vortex downstream and it took a long distance to recover this turbulence and become laminar flow again.

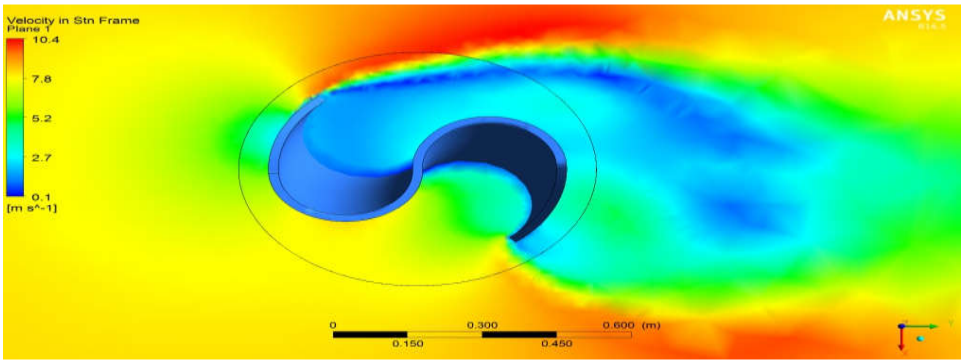

Figure 17. Velocity distribution SHAWT at twist angle 90 degrees

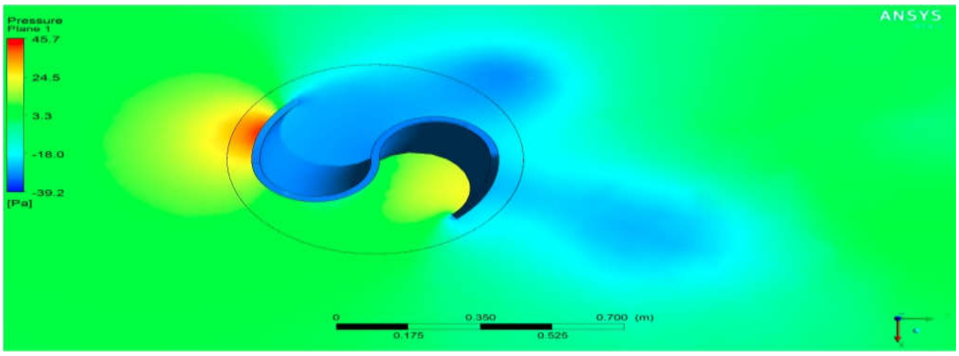

Figure 18. Pressure distribution SHAWT at twist angles 90 degrees dedegrees

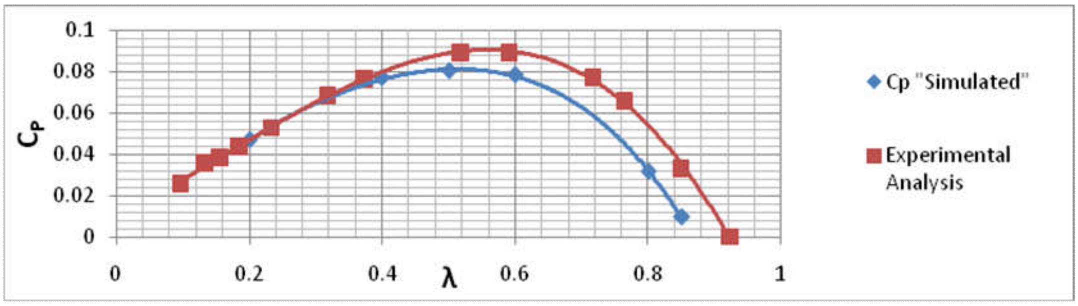

Figure 19. (C_pVersus λ) for Experimental SHWT single blade and Computational fluid dynamics blade at helical of twist angle 90 degrees

2.Pressure Distribution, Figure(18)

A.The flow upstream

According to the velocity distribution, the air flow from the left hand side "upstream "to the right hand side "downstream," with velocity 8.5m/sec and pressure 3.3 Pascal (Green color). Then, when the air flow incident the wind turbine at a point, it causes sudden impact that lead to the turbine at stagnation point where the kinetic energy is converted to pressure energy that leadsto increase in pressure to 45.7 Pascal (Red Color) and this is shown at the point outside the bucket of the turbine.

B.The flow of air over the turbine

Due to the increase of the rotational speed of the wind turbine, the pressure decreases again and reaches negative pressure when the air flows through the Helix of the S-Shaped Wind Turbine. This is due to the formation of vortex and the pressure varied from -39.2 to -18 Pascal (Blue Color) inside the buckets of the turbine due to swirl motion.

C.The flow downstream

The air flow downstream the vortex increases due to the variation of velocity that leads to pressure drop -18 Pascal(Baby blue) for a distance till the vortex disappears and return again to the normal pressure at the given speed 3.3 Pascal(green Color)

Comparison between SHAWT single blade at twist angle90 degree for the experimental and computational fluid dynamics as in Figure (19)

- It was found that the two curves are almost of the same trend and a fair agreement was achieved between them. At low rotational speed, and as the rational speed increases the experimental curve go higher than the (CFD) Analysis Curve and this is because the meshing is based on estimate trial **(12-17)** and the system is a closed system with upstream flow is at distance 5D from the turbine and the downstream is 10Dwhich is not enough to recover this turbulence and become laminar flow again. While the system (Duct Design) in the Experimental Analysis is an open system, not closed system, so the effect of vortex downstream the S-Shaped wind turbine vanishes is faster.

- The performance in the experimental analysis is higher than the CFD Analysis at higher rotational speed.

Comparison between SHAWT and pervious work

Comparison of SHAWT single bladeversusM.A KamojoHelical Savonius Rotor (10) at helical of twist angle 90°Figure (20-23)

- M.A Kamojo Helical Savonius (10) at helical of twisted angle 90 degrees with dimensions 0.25m height and 0.25m at diameter and tested at wind speed 8 m/sec.
- This comparison shows that the power coefficient M.A Kamojo Helical Savonius Rotor (14) is higher than Experimental S-Shaped Helical Horizontal Axis Wind Turbine at (C_P) 0.165 at(λ) 0.7.

Figure (20) Single blade at twist angle 90°

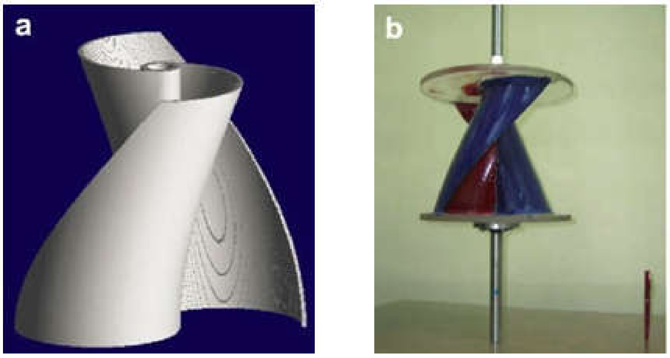

Figure (21) M.A kamojo Helical Savonius Rotor [10] with twisted angle 90°

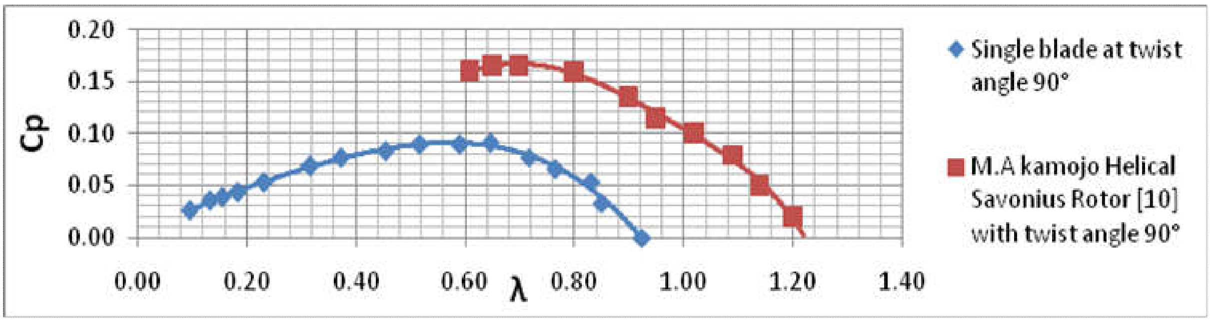

Figure 22. Comparison of present work &M.A kamojo Helical Savonius Rotor [10] at twist angle 90 degrees

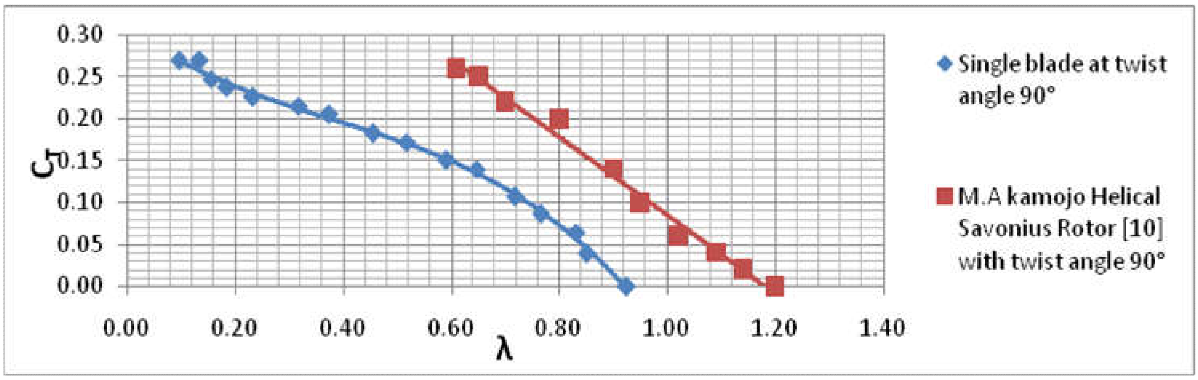

Figure 23. Comparison ofpresent work and M.A Kamojo Helical Savonius [10] at twisting angle 90°

- While torque coefficient of Experimental S-Shaped Helical Horizontal Axis Wind Turbine is Higher than M.A Kamojo Helical Savonius Rotor (10) where (C_T) 0.27 at (λ) 0.096 and the present work covers a smaller range of the tip speed ratio compared with the other investigator.

Conclusion

1. Double blade S-Shaped Helical Horizontal Axis Wind Turbine at helical profile 120 degrees gives the highest performance and the highest torque coefficient.
2. Double blade S-Shaped Helical Horizontal Axis Wind Turbine has higher torque coefficient than single blade at same helical profile
3. The single and double blade S-Shaped Helical Horizontal Axis Wind Turbine at helical profile 180 degrees had the lowest performance and torque coefficient
4. The single S-Shaped Helical Horizontal Axis Wind Turbine has higher torque coefficient at helical profile of twisted angles 90 degrees than helical Savonius.
5. The S-Shaped Helical Horizontal Axis wind turbine is a type of low wind speed wind turbine with high performance.

Nomenclature

A: Projected area of the rotor (m^2)
C_p: Power coefficient
C_T: Torque coefficient
CFD: Computational Fluid Dynamics
D: Rotor diameter (m)
H: Rotor height (m)
HAWT: Horizontal Axis Wind Turbine
N: Rotor rotational speed (rpm)
P_{av}: Available power (W)
P_{net}: Net power from the turbine (W)
T: Torque (J)
T_1: Tension force at fixed side (N)
T_2: Tension Force at adjustable side (N)
TSR: Tip speed Ratio
V: Upstream air velocity (m/s)
VAWT: Vertical Axis Wind Turbine
SHAWT: S-Shaped Helical Horizontal Axis Wind Turbine
ρ: Air density (kg/m^3)
ω: Rotational speed in (rad∕s)
λ: tip speed ratio

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