INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
S. Kumar R et al., Vol.8, No.3, September, 2018

# Numerical Analysis of Different Blade Shapes of a Savonius Style Vertical Axis Wind Turbine

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*Received: 05.06.2018 Accepted: 22.07.2018*

**Abstract-** The objective of this present numerical work is to evaluate and compare the performance of the proposed outer overlap Bach type rotor with conventional simple Savonius rotor and modified Bach type rotor. In order to improve the performance of the modified Bach type rotor at low wind speed regimes, the outer overlap Bach rotor is proposed. Modeling and discretization of the computational domain with mesh is carried out using GAMBIT 2.4 and the analysis is performed using ANSYS FLUENT 14.5. SST k-ω turbulence model is used to achieve the closure for the governing equations. The different blade shapes of the rotors are tested at same free stream conditions and the performance characteristics curves are plotted along with contours to visualize the flow physics over the rotor. The proposed outer overlap Bach type rotor showed an improved performance by 15% in terms of coefficient of power over the existing modified Bach type rotor. $C_{p(max)}$ of about 0.48 is obtained at a tip speed ratio of 0.60 by the proposed outer overlap Bach rotor.

**Keywords** Vertical axis wind turbine, Savonius style, outer overlap Bach type rotor, modified Bach type, computational fluid dynamics

## 1. Introduction

The impact on environment by usage of fossil fuels has become a major threat to the world than the economic growth due to the fossil fuels usage. Electricity connects the relation between the fossil fuel usage and economic growth. Global industrial revolution and the rate of increase of urbanization in developing countries have further increased the usage of fossil fuels. The way in which electricity is generated impacts the quality of environment. The present need is to sustain the economic growth. But, this is to be achieved without any damage to the environment by reducing the usage of fossil fuel and electricity generation by alternate renewable sources of energy. The energy requirements are broadly classified into residential load and industrial load. Many researches are carried out on renewable energy source, which is an alternative source of energy that impacts less on the environment. Wind energy is an alternative energy source, which properly harnessed can meet the residential energy needs. Vertical axis wind turbine (VAWT) is a one that can fulfill this need. Based on the principle force that is responsible for the rotation of blades, vertical axis wind turbines are classified into two categories namely, lift based Darrius type turbines and drag based Savonius type turbines. Savonius VAWT, also known as a drag-driven device, has the only driving force which is due to difference in wind drag acting on its blades (one is convex and other concave) [1]. However, Modi and Fernando [2, 3] observed the role of lift force in overall torque generation at low angle of attack. Therefore, Savonius VAWT is solely not a drag driven device but a blend of drag as well as lift driven device. Thus, the power coefficient $C_p$ goes beyond the limit set i.e., 0.08 for a purely drag based machines.

Finnish engineer Sigurd Johannes Savonius [4] first developed the modern VAWT. Recently, much focus is given to this type of VAWT due to the viability of using small scale turbine in urbanized areas to meet the specific energy demands. The main advantages of Savonius turbines is its high starting torque [5], simple in design, low cost, compact in size, easy to install, good starting abilities, capability to operate independently in a wide range of wind directions [1, 6-14], and relatively low operating speed [1, 6-14]. All these aspects make Savonius VAWT a right choice to meet the residential energy needs. High negative torque produced by the returning blade and low efficiency are the drawbacks of Savonius turbines. Efforts are made constantly by various researchers to seek designs to ensure better rotor performance. Sukanta Roy and Saha [14] experimentally tested the newly developed two bladed Savonius rotor in a wind tunnel and the new design showed an improved performance over the other standard blade types such as semi elliptic, semi circular, Bach and Benesh tested under identical conditions. The study revealed a maximum $C_p$ gain of 34.80% with newly developed two bladed Savonius rotor compared to conventional Savonius VAWT.

Saha and Jaya Rajkumar [15] experimentally tested the possibility for use of twisted three bladed rotors for producing power and compared the results with simple conventional semi circular bladed Savonius rotor. Experimental study proved the ability of twisted rotors with its higher efficiency, self starting capability along with smooth running compared to conventional type. Also, the twisted blades produced around 30% higher $C_{p(max)}$. Keum Soo Jeon *et al.* [16] used helical blades with varied sizes and shapes of end plates in their experimental work to analyze whether the end plates enhanced the aerodynamic performances of the helical Savonius VAWT by comparing the results with helical Savonius rotor without end plates. Maskell's blockage correction method was applied in this study and a performance improvement of 36% $C_p$ was obtained by helical Savonius rotors with both lower and upper end plates. Also, $C_p$ linearly increased with increase in end plate area.

VAWT is influenced by many key factors like shape of the blades, number of blades, phase shift angle and overlap ratio. Kumbernuss *et al.* [17] experimentally studied the relationship of overlap ratio (β) and phase shift angle of double stage three bladed Savonius rotors. After experimentation, it was established that overlap ratio directly influenced the overall performance and the highest performance was obtained with an overlap ratio 0.16. The performance of turbine was affected by phase shift angle depending majorly on air velocity. At 0° to 360° rotor angle, conventional Savonius rotor does not start on its own at certain rotor angles as the coefficient of static torque is negative. To overcome this, Kamoji *et al.* [18] proposed and investigated the helical Savonius rotors with a 90º twist. The performance of helical rotors with shaft between the end plates and without shaft between the end plates at different overlap ratios are compared with the performance of conventional Savonius rotor. Helical Savonius rotors had positive coefficient of static torque at all the rotor angles and the same type without shaft showed very good performance. Damak *et al.* [19] tested helical Savonius rotors with 180º twist in a wind tunnel to determine the optimum aspect ratio. An aspect ratio of 1.57 showed good performance irrespective of Reynolds number. Khandakar Niaz Morshed *et al.* [20] analyzed a semi cylindrical three bladed Savonius rotor experimentally in a low speed wind tunnel as well as numerically by using CFD techniques. Based on the study, the authors concluded that at higher Reynolds number operation, the turbine without overlap ratio gave better aerodynamic coefficient values. On the other hand, at lower Reynolds number, the rotor with moderate overlap ratio gave better result. Interestingly, Patel *et al.* [21] numerically investigated the effect of optimum overlap ratio of Savonius style vertical axis hydro turbines for three different overlap ratios and found that an overlap ratio of 0.2 produced maximum torque. Giovanni Gerardo Muscolo and Rezia Molfino [22] proposed a novel blade design called Brozinus VAWT and compared the numerical results of Broznius with conventional Savonius VAWT. Broznius type VAWT showed good performance with its $C_p$ value higher than the values of Savonius and Kyozuka turbines.

Interaction between Savonius turbines held in a cluster increased the power of individual rotors. As seen in vertical axis wind turbine farms, Mohammed Shaheen *et al.* [23] investigated the clusters of two Savonius rotors arranged in parallel and oblique positions as well as three rotors arranged in triangular clusters. Numerical analyses over these configurations were performed to determine the optimum gap distance and setting angle between the adjacent rotors for maximum $C_p$. Two turbine oblique clusters were used to develop an efficient triangular shaped three turbine clusters which showed an improved $C_P$ of about 34% compared to a standalone Savonius rotor. Jae-Hoon Lee *et al.* [24] carried out tests on Savonius turbines with four different twist angles. The test was carried out numerically and 45º twist angle was found to be the optimum one at which maximum $C_p$ occurred. Mohamed *et al.* [25] performed numerical studies on optimization of Savonius turbine with an obstacle shielding the returning blade. Both two bladed and three bladed Savonius rotors without and with obstacle shield were studied. $C_p$ improvement of 27.3% and 27.5% was obtained for two blade and three blade with shield. Two blade rotor with an obstacle shield proved to be an optimal configuration than three blade rotor.

David Afungchui *et al.* [26] developed a code to study the aerodynamic behaviour of a Savonius rotor based on two dimensional discrete vortex formulations. The authors validated the code by comparing the experimental data with numerical results. João Vicente Akwa *et al.* [27] numerically studied the effect of overlap ratio on power and moment coefficients. Results from the study concluded that an overlap ratio of 0.15 gave the maximum power coefficient. Nasef *et al.* [28] performed an aerodynamic studies on stationary and rotating Savonius VAWT for different overlap ratios. Suitable turbulence model was selected by comparing the simulation results with available experimental data. SST k-ω turbulence model gave accurate results and maximum performance was obtained with overlap ratio of 0.15. Numerical investigations on conventional, Bach type and elliptical blade shapes were carried out by Konrad Kacprzak *et al.* [29]. The study revealed the significance of applying laminar turbulent transition model. All the rotors attained $C_{p(max)}$ at a tip speed ratio of 0.80. Bach type rotor was found to the best among the tested rotors in terms of power coefficients. A better power characteristics were exhibited by an elliptical Savonius turbine compared to the classical one. El-Askary*et al.* [30] studied the Savonius rotor with an overlap ratio of 0.15 having three different improved wind direction control designs that forced the wind towards the concave side of returning blade to eliminate the negative torque. SST k-ω turbulence model was used to simulate the turbulence behaviour. Tong Zhou and Dietmar Rempfer [31] conducted numerical studies using realizable k-ε turbulence model on flow field along with its aerodynamic performance over a Bach type rotor and conventional Savonius rotor. Bach type rotor showed a better performance with power and torque coefficient compared to conventional Savonius rotor. Similarly, McTavish *et al.* [32] made numerical analysis on flow behaviour of Savonius rotor.

The performance of Savonius rotor is influenced by important geometrical parameters namely aspect ratio (AR), overlap ratio (β), tip speed ratio (λ), blade arc angle (φ), Reynolds number (Re), number of blades, gap ratio (γ) and use of end plates. From the above mentioned literatures, it is understood that a lot of research were carried out on these parameters that influence the performance of a Savonius rotor. A significant improvements in the performances of the Savonius rotors were also reported by several researchers through optimization of these parameters. It is understood that overlap ratio (β) is one of the very important parameter that determines the performance of Savonius rotor. The major advantage of Savonius VAWT is its simple design and its ability to operate in a wide range of wind directions. Few investigators carried out studies using twisted and helical blades with perceptible gain in performance using complex design involving the blades [15, 16, 18, 19, and 33]. Therefore, modifications in blade design by creating complexities are to be avoided. Studies with modified blade shapes [2, 14, 29, 31, 34-41] were earlier attempted by researchers with encouraging results. This led the researchers again with renewed interest to perform further detailed studies on these blade designs [42-48]. Presently, computational fluid dynamics (CFD) is used as a tool in these efforts to design the blades that ensure an improved rotor performance.

The objective of this present comparative study is to improve the performance of the Savonius rotor as well as its starting characteristics with novel shapes of the blade. The numerical investigations are performed using ANSYS Fluent. Different shapes of blades, namely classical semi-circular, Bach type rotor and the proposed innovative Savonius style outer overlap Bach type rotor are studied. All these Savonius style rotors are analyzed at identical conditions to have a better comparison with classical Savonius rotor. Also, comprehensive wake analyses of these rotors are discussed along with the performance indicators.

## 2. Description of Blade Profiles

In this present study, three different blades shapes of Savonius style VAWT, as shown in Fig. 1, are chosen. The diameter of the rotor (D) is assumed to be 150 mm and the aspect ratio (AR), which is the ratio of height of the rotor (H) to diameter of the rotor (D), is 1.0. The diameter of the end plates is kept 1.10 times D, as per Sunkanta Roy and Saha [14]. Based on the earlier researches [1, 6, 14], it was established that an overlap ratio (β) of 0.20 for classical semi-circular Savonius rotor gives better performance in terms of power coefficient as well as torque coefficient. The dimensional detail of classical semi-circular Savonius rotor is shown in Fig. 1(a).

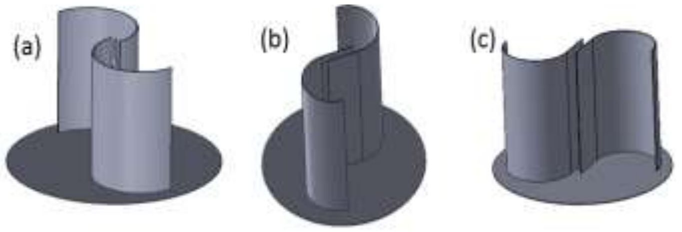

**Fig. 1.** 3D model of (a) Classical semi-circular Savonius rotor (b) Modified Bach type rotor (c) Proposed outer overlap Bach type rotor.

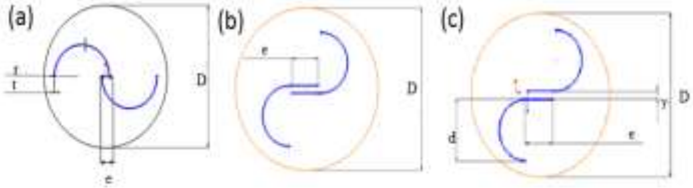

**Fig. 2.** 2D model of (a) Classical semi-circular Savonius rotor (b) Modified Bach type rotor (c) Proposed outer overlap Bach type rotor.

**Table 1.** Dimensional detail of all the models

| | |
|---|---|
| Overlap distance for the classical semi-circular Savonius rotor (e) | 2.25 mm |
| Overlap distance for modified Bach type rotor (e) | 30 mm |
| Overlap distance for proposed outer overlap Bach type rotor (e) | 30mm |
| Thickness of the blade (t) | 1 mm |
| Radius of the blade (r) | 37.5 mm |
| Diameter of the end plate (D) | 165 mm |
| Chord length of the blade (d) | 75 mm |
| Gap ratio (γ) | 10 mm |

As modified Bach type rotor showed an improved values of power coefficient and torque coefficient over classical Savonius rotor, this type is also chosen for this present study [36]. The modified Bach type rotor studied by Roy and Saha [36] is a variation of the Bach type rotor studied by earlier researchers [2, 35]. Roy and Saha [36] as well as Modi and Fernando [2] established that blade arc angle (φ) of 135° was found to be an optimum parameter. Figure 1(b) shows the dimensional detail of the modified Bach type rotor with an overlap ratio (β) of 0.40 [14, 36]. Figure 1(c) shows the newly conceived Savonius style blade profile named outer overlap Bach type. In the modified Bach type rotor, the overlap is maintained inward where as in the proposed type, the overlap is kept outward as seen in the Fig. 1(c). The outward overlap ratio (β) is also kept as 0.40 with a blade arc angle (φ) of 135°. The dimensional details of these three different types of blades are given in Table 1 along with the inscriptions in Fig. 2. The presence of end plates prevents the loss of aerodynamic torque which is generated by the blades. It is understood that higher aerodynamic performance is ensured by having a larger circular end plate area [1, 12, 16]. This is due to improved pressure differences between the two blade surfaces (convex and concave). The diameter of end plate ($D_o$) for both the top and bottom plates are kept 1.10 times the diameter of the rotor (D) for an aspect ratio (AR) of 1.0 [14, 39] for all the models.

## 3. Computational Domain and Boundary Conditions

As the present numerical analysis is two dimensional, the mid plane of the test section is considered for the study. The computational domain for the present study is a rectangular domain. The dimensions detail of the computational domain in terms of diameter of the rotor is shown in Fig. 3. As seen in the Figure, the rotating zone represents the zone of rotation whose dimension is equal to the end plate diameter ($D_o$). The stationary zone represents the outer walls of the wind tunnel test section. The $y^+$ value is maintained less than 1. The height of the first cell is 0.0010 and the growth factor is kept as 1.2 and 15 layers are in maintained in the boundary layer regions to capture the viscous effects. The top and bottom portions of the stationary domain are discritized by MAP scheme using structurally meshed quadratic elements near the wall regions whereas other portions are meshed using PAVE scheme as shown in Fig. 4.

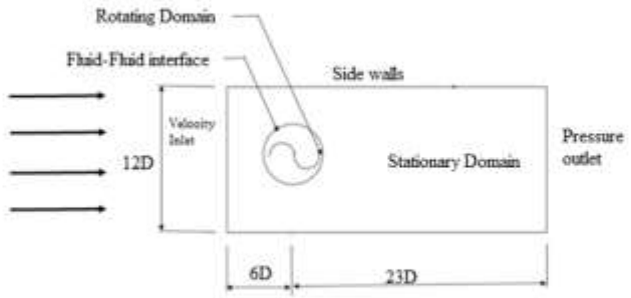

**Fig. 3.** Computational domain with boundary condition details

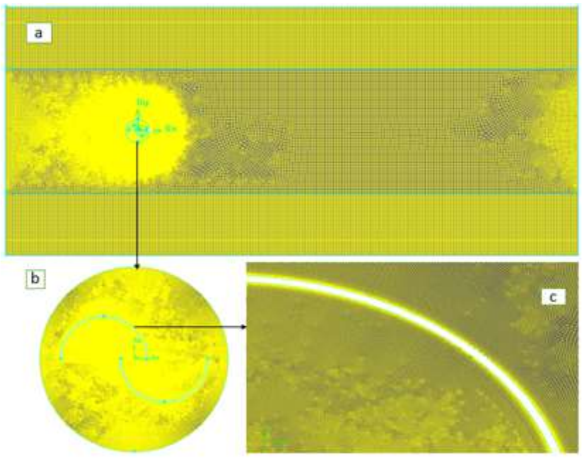

**Fig. 4.** (a) Meshed computational domain (b) Closer view of the rotating zone (c) Near wall meshing of blades

The grid independency study is carried out to ensure that the results are independent of the mesh and the details are shown in Table 2. The variation of mesh elements with performance coefficients is also shown in Fig. 5 and the total number of nodes chosen for this present study is 342421. The boundary conditions at the top and bottom portions are enforced with wall type conditions. At the interface region between the rotating zone and the stationary zone, a fluid-fluid type of interface is applied. The walls of the rotor blades inside the rotating zone are mentioned as wall type boundary condition. The inlet is enforced with velocity boundary condition with its value equal to 6 m/s and the outlet is enforced with total pressure equal to 1 atm. Shear Stress Transport (SST) k-ω turbulence model which accurately predicts the adverse pressure gradients over the blades as suggested by Mohammed Shaheen *et al.* [23] is enforced here. The rotating zone is simulated using sliding mesh model (SMM) with semi-implicit pressure linked equations [SIMPLE] algorithm. The discretization of the governing equations and the equations corresponding to the turbulence model are of second order upwind scheme [23]. The time step is set to 5.89e-5 in order to accurately predict the performance indicators. This time step is chosen such that the time step corresponds to one degree rotation of rotor. The same time step is chosen for all the tip speed ratios involving various blade shape configuration [31]**.** The convergence criterion for all the governing equations is set to$10^{-5}$.

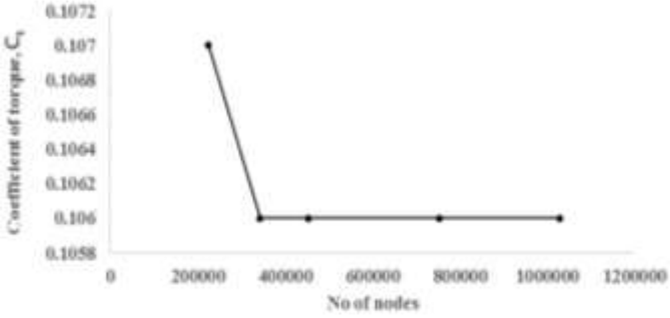

**Fig. 5.** Variation of $C_t$ value with mesh elements

**Table 2.** Grid independency study

| No. of nodes | Coefficient of torque ($C_t$ ) | Coefficient of power ($C_p$) |
|---|---|---|
| 224598 | 0.107 | 0.2675 |
| 333551 | 0.107 | 0.2673 |
| 342421 | 0.106 | 0.2659 |
| 402213 | 0.106 | 0.2657 |
| 752463 | 0.106 | 0.2648 |
| 1027431 | 0.106 | 0.2648 |

## 4. Validation

In addition to the grid independency study discussed in the previous section, the validation of numerical simulation data is also carried out with the available experimental result [28]. Figure 6 shows the validation of the coefficient of power ($C_p$) of a simple Savonius style VAWT done in this present simulation study with the experimental result [28]. It is observed that the deviation of 6.5% with the experimental results is found to be reasonable. Hence, with this confidence, further simulations are carried out with different blade shapes of a Savonius style vertical axis wind turbine and their flow physics are discussed in the next section.

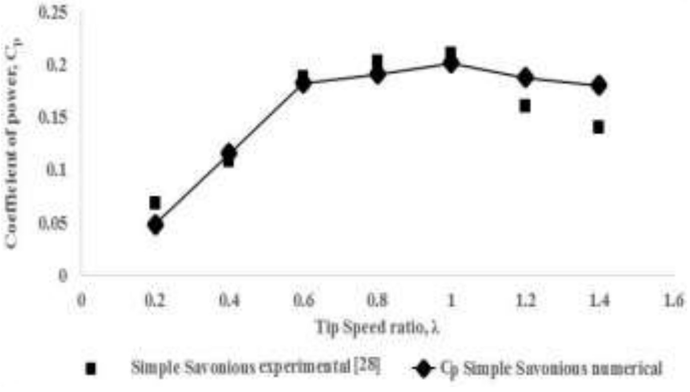

**Fig. 6.** Validation of numerical data with the experimental result [28]

## 5. Results and Discussion

The purpose of this study is to examine the effects of blade shape on the performance characteristics of the wind turbine for a particular wind speed, namely 6 m/sec. The performance of the proposed outer overlap Bach type design is compared with other existing type of rotors available in the literature [18].

### *5.1. Power Coefficient Vs Tip Speed ratio*

Figure 7 shows the variations of coefficient of power for different tip speed ratios varying from 0 to 1.40. As observed from Fig. 7, the Savonius rotors performance fall beyond the tip speed ratio of 1. This fall in the coefficient of power can be explained aerodynamically as the tip speed ratios reaches beyond the value of 1. The angular rotational speed of the rotor is higher than the velocity of the wind. So, wind passes the turbine without fully striking the rotor, resulting in a decrease in torque. This is the reason behind the tip speed ratio being limited to 1 for simple Savonius rotor. Similar trend is also observed in the experimental results [28] with a peak $C_p$ value of 0.25 at the tip speed ratio of 1. The Bach type rotors are good in terms of performance at all the tip speed ratios. A peak performance is obtained at a tip speed ratio of 1 in the case of outer overlap type rotor. Beyond λ= 1, the coefficient of power of the proposed outer overlap Bach type rotor also falls. A $C_{p(max)}$ of 0.48 is reached at a tip speed ratio of 0.60. But, in both the case of classical Savonius and modified Bach type rotors, the maximum coefficient of power is reached at the tip speed ratio of 1. The modified Bach type rotor gives the peak performance at this free stream wind speed of 6 m/s. Moreover in the proposed outer overlap Bach type, an improved performance by around 15% is observed at the tip-speed ratio of 0.60. The reason for this peak performance is due to the outer overlapping of the blades and further explanation on this is discussed in the later section.

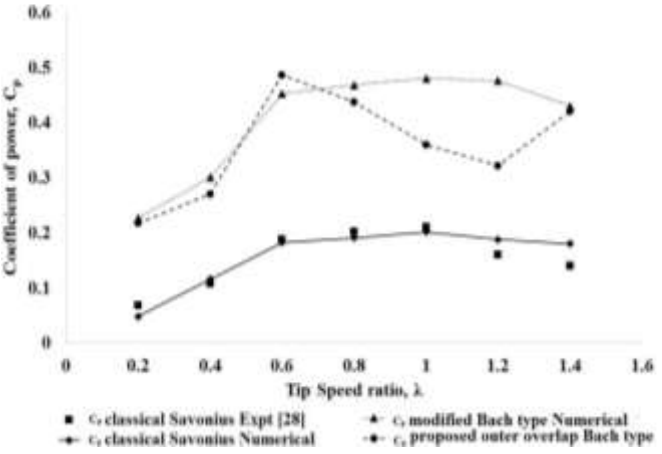

**Fig. 7.** Variations of coefficient of power with tip speed ratio

Moreover, the proposed outer overlap Bach type is compared with the earlier work done by Zhang Baoshou *et al.* [49]. The peak $C_p$ obtained by Zhang Baoshou *et al.* [49] is 0.259 at λ = 1.0. On the other hand, the proposed outer overlap configuration in this present study develops a $C_p$ of 0.349 at λ = 1.0. It is observed that the $C_p$ of the proposed outer overlap Bach type configuration improved by nearly 34.75% when compared to the optimal Savonius study by Zhang Baoshou *et al.* [49].

### *5.2. Torque Coefficient Vs Tip Speed ratio*

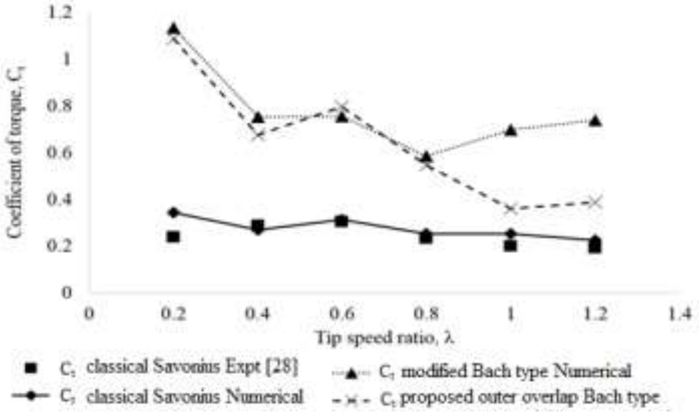

**Fig. 8.** Variations of coefficient of torque with tip speed ratio

Figure 8 shows the variations of the coefficient of torque at various tip speed ratios. In general, the coefficient of torque falls gradually as there is an increase in the tip speed ratios. This may be due to decrease in the drag force in the rotor at higher rotational speeds or higher tip speed ratios of the rotor. The reason for this reduction in the drag values is mainly due to reduction in pressure and viscous forces because of lesser contact surface area of the incoming wind with the turbine surface. For the case of the proposed outer overlap Bach type rotor, the peak performance in terms of coefficient of torque is reached at a tip speed ratio of 0.60. Based on the earlier literatures [2, 35, 36], it is understood that the Bach type rotor is best suited for low speed wind. Moreover, higher torque is produced at low rotational speed in the modified Bach rotor type. In order to get the maximum power, the turbine has to be rotated at higher rotational speeds. Similarly, to obtain high torque, the turbine has to be rotated at lower rotational speeds. The major advantage of this proposed outer overlap Bach type rotor is that both high torque and high power coefficients are obtained at low rotational speeds of the rotor. It is one of the major advantages of this proposed outer overlap Bach type rotor. Moreover, the structural damage of the blades can also be reduced due to its lower angular velocity. Hence, the flattering caused by the blades is also reduced.

### *5.3. Pressure and Velocity Contours*

In order to have a good understanding of the blade arrangement in the rotors, the pressure and velocity contours of these rotors are studied as shown in Fig. 9. It is understood that the disturbance created due to the rotational effects of the rotor, affects the incoming velocity to the rotor. When the rotor rotates, its projected area forms a circular projected solid disc. So, the incoming flow field gets diverted without properly hitting the turbine blades. This cumulative effect passes to some distance in the flow field upstream. It is similar to the rotational effects caused by the propeller of an aircraft. This phenomenon is observed in the velocity vector as shown in Fig. 10.

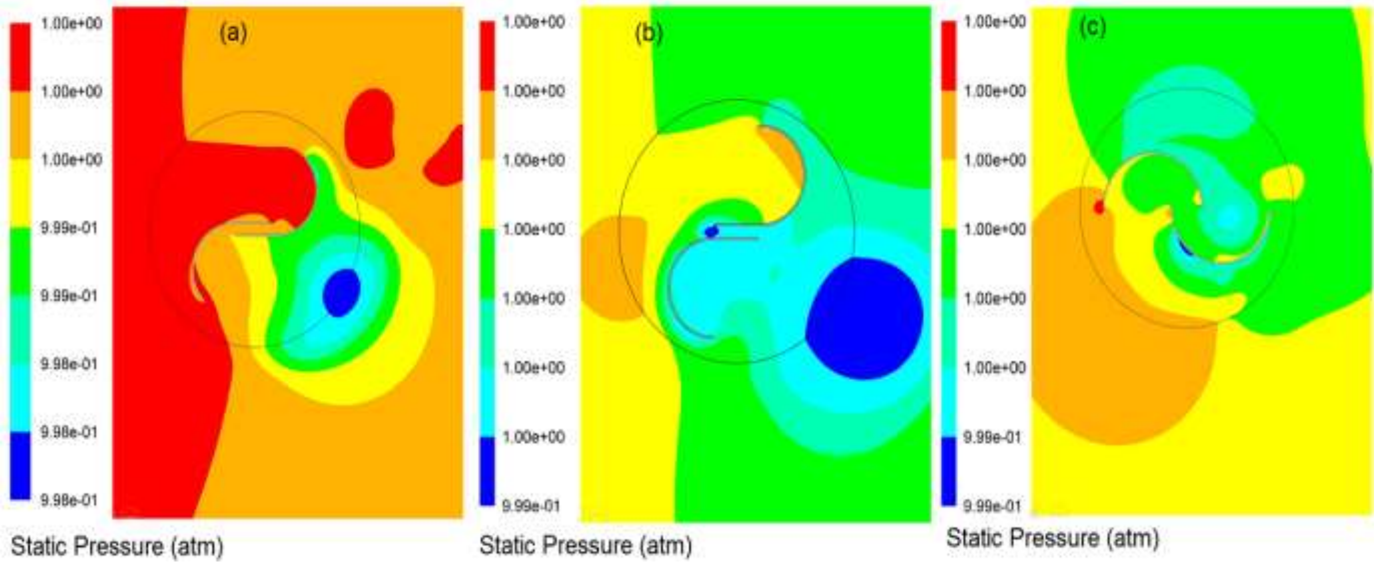

**Fig. 9.** Pressure contours (a) Modified Bach type rotor (b) Proposed outer overlap Bach type rotor (c) Classical Savonius rotor

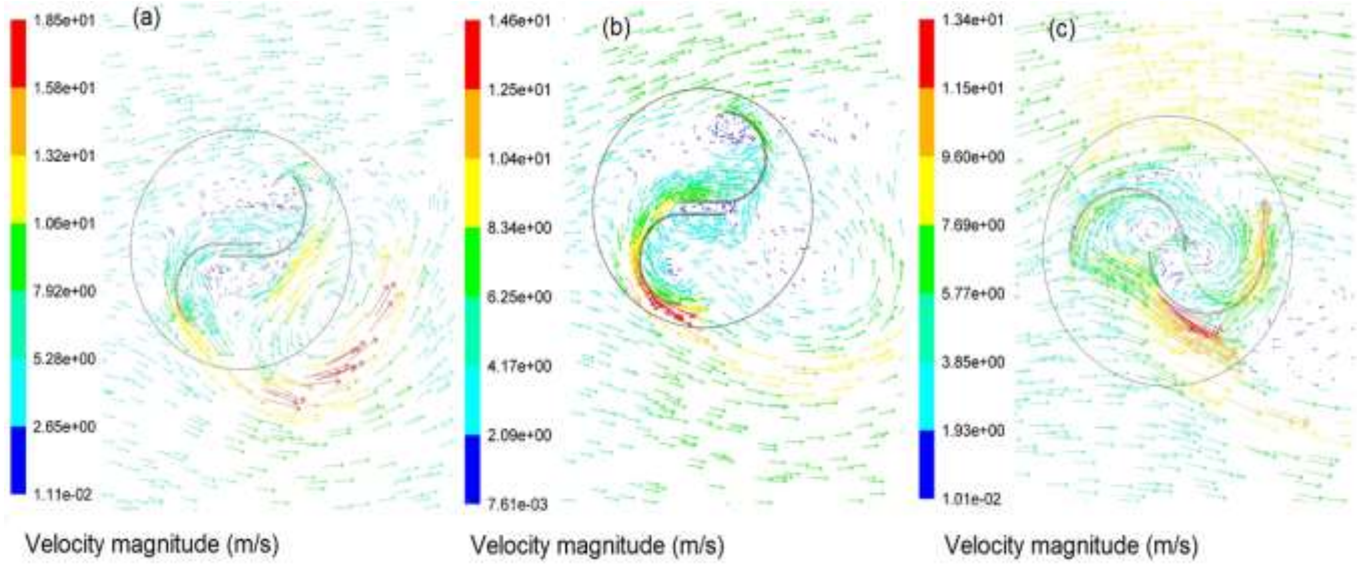

**Fig. 10.** Velocity vectors (a) Modified Bach type rotor (b) Proposed outer overlap Bach type rotor (c) Simple Savonius rotor

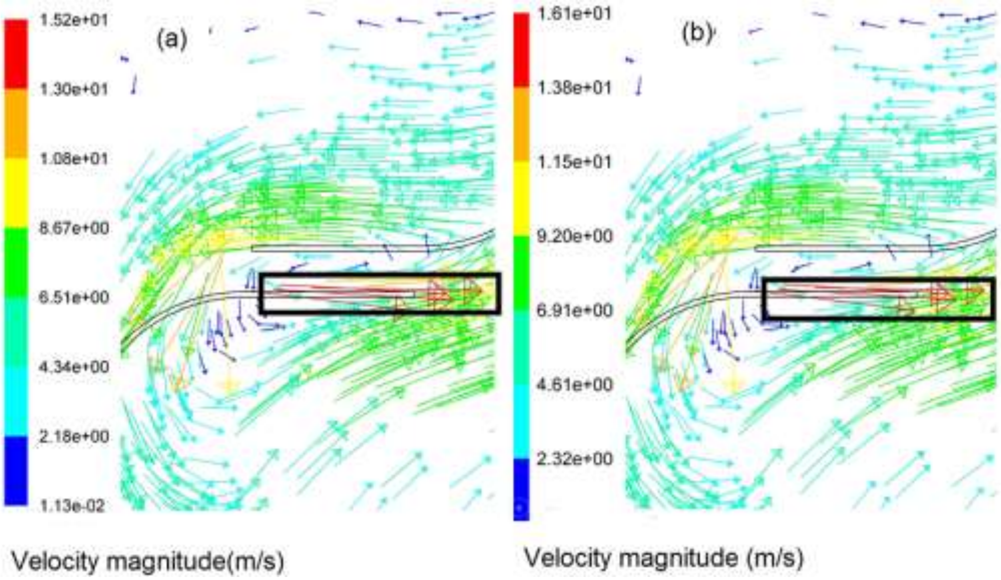

**Fig. 11.** Accelerating passage due to overlapping in outer overlap Bach type for λ = 1.2 and λ =1.4

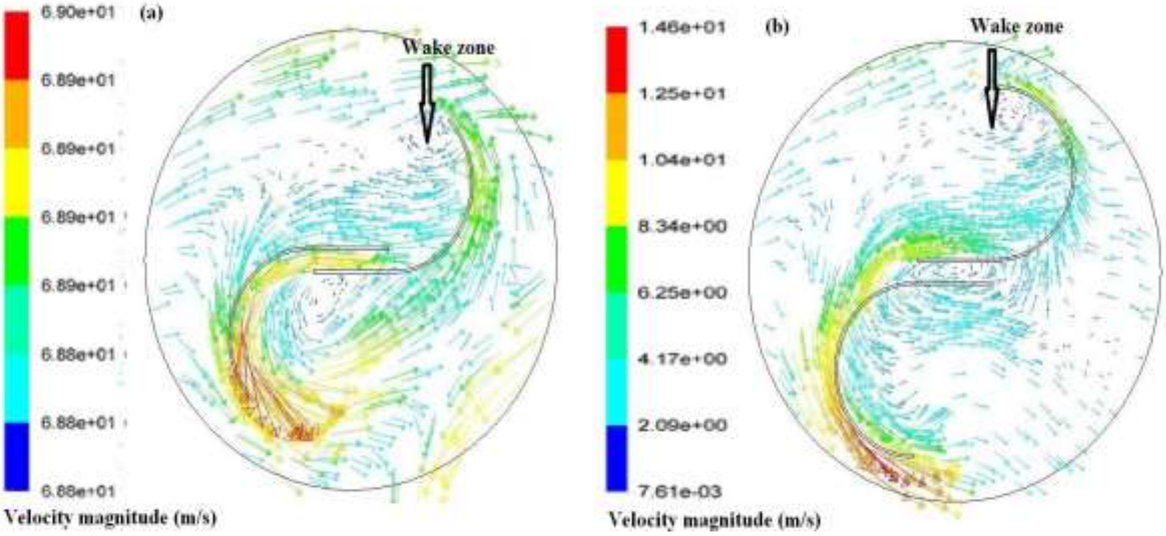

**Fig. 12.** Shifting of wake regions for modified Bach type and outer overlap

As seen in Fig. 10, the velocity in between the overlap passage of the proposed outer overlap Bach type blade is locally higher than the free stream velocity. So, the torque developed by this turbine is relatively higher than the other type of turbine blades. The overlap distance acts as an accelerating passage for the flow to get accelerated within the overlap distance and the flow reaches a velocity of 8 m/s as can be seen in the Fig. 10. A wake region is observed closer to the concave side of the advancing blade. So, all the kinetic energy in the flow field that acts on the blade is transformed into pressure energy. However, as the tip speed ratio is increased, this wake region moves away from the concave side of the advancing blade. So, less energy is transferred from the flow field to the turbine blades. This could be the reason for the decrease in the torque coefficient**.** Also, the surface area of the incidence to the incoming flow is much higher in both Bach type rotors as compared to classical Savonius rotor.

It is known that the pressure and viscous forces also depends on the surface area of the rotor. Accelerating passage because of overlapping of blades for Bach type rotor extends over the entire returning blade. So, the net torque produced by the Bach type rotor is higher than the simple Savonius rotor. As can be seen in Fig. 11 for outer overlap Bach type, the maximum velocity of the flow is observed at the convex sides of the rotor which is due to combining of the flows over both sides of the rotor blades. An increase in tip speed ratios also reduces the pressure at the convex surfaces of the rotor as seen in Fig. 11, which lead to a reduction in torque being produced. It is observed that at a tip speed ratio of 1.20, the pressure at the positive side of the rotor is much higher when compared with a case of tip speed ratio 1.0. This may be the reason for the modified Bach type rotor giving a better torque output even beyond tip speed ratios of 1.0 as shown in Fig. 8.

The overlap distance in case of the Bach type rotor is 41% of its chord length of the rotor. Due to this, the accelerating flow passage gets an extended length when compared to classical Savonious rotor. So, the flow is accelerated better through this passage of Bach type rotor which in turn strikes the positive side of the returning blade of Bach type rotors. This concept is also shown and explained using Figure 11. Therefore, the performance of Bach type rotors (modified as well as proposed outer overlap) is better than the classical Savonious rotor.

It is observed, as seen in Fig. 12, that the wake region is shifted towards the tip of the blade due to better acceleration in the Bach type as the tip speed ratio is increased. Similar trend is also observed in the simple Savonius rotor but, the location of wake region is near to the center of the rotor unlike near the tip as observed in Bach rotor type.

The major advantage of this proposed outer overlap Bach type rotor model is that the peak performance is obtained between tip speed ratio of 0.40 and 0.60. The peak coefficient of torque is also obtained between this range. The disturbance caused by the negative side of the blade (i.e., returning blade) travels towards the positive side of the rotor. Simultaneously, some of the disturbance from this negative side is also forced through the blade overlap distance. Moreover, it is a passage open to the incoming flow whereas in the existing modified Bach type rotor, there is no passage to flow for the incoming flow.

Therefore, this design modification in the rotor arrangement leads to a better performance in terms of $C_p$ and $C_t$ for the proposed outer overlap Bach type rotor.

## 6. Conclusion

The comparative numerical analysis of flow over different blade shapes of Savonius style VAWT is carried out and its detailed flow behaviour are studied. The key observations from this present work are given below:

- The maximum coefficient of power obtained by simple Savonius rotor is 0.25 at a tip speed ratio of 1.0 whereas for the modified Bach type, the $C_p$ is 0.35 which is obtained at a tip speed ratio 0.8. The $C_p$ for the proposed outer overlap Bach type is 0.48 at a tip speed ratio of 0.60.
- At low wind speed regimes, high performance is observed for the proposed outer overlap Bach type rotor.
- Maximum torque coefficient for simple Savonius rotor, modified Bach type rotor as well as the proposed outer overlap Bach type is obtained at a tip speed ratio of 0.20.
- A $C_{p(max)}$ of about 0.48 is obtained at a tip speed ratio of 0.60 by the proposed outer overlap Bach rotor.

Based on these observations, the proposed outer overlap Bach type rotor is better in terms of performance when compared with all the other blade types.

## Nomenclature

| | |
|---|---|
| H | Height of the rotor (m) |
| D | Diameter of the rotor (m) |
| AR | Aspect Ratio (H/D) |
| $D_0$ | Endplate diameter (m) |
| N | Rotational speed (rpm) |
| R | Radius of the rotor (m) |
| T | Static torque (Nm) |
| P | Power produced by rotor (kW) |
| $P_{av}$ | Power available in the wind (kW) |
| $U_\alpha$ | Free stream velocity (m/s) |
| e | Overlap distance (m) |
| d | Chord length of the rotor blades (m) |
| t | Thickness of the rotor (m) |
| β | Overlap ratio (e/d) |
| ω | Angular speed of the rotor (rad/sec) |
| γ | Gap ratio (m) |
| ρ | density of air (kg/m$^3$) |
| $C_p$ | Coefficient of power ($C_p = C_t * \lambda$) |
| $C_t$ | Coefficient of torque ( $C_t = \frac{4T}{\rho U^2 D^2 H}$) |
| TSR | Tip Speed ratio ($\lambda = \frac{\omega R}{U} = \frac{2\pi N R}{60 U}$) |

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