ISSN No:-2456-2165

Influence of Design Parameters on the Performance of Savonius Wind Turbine

Priyam Deka
Department of Mechanics and Systems
University of Tours,
Tours, France

Abstract:- In this era of technological advancement, the demand for energy requirements is increasing globally. With a limited stock of fossil fuels and the pollution issue related to the burning of these fuels, the world needs to find an alternative of it, which must be cleaner and greener. This is where wind energy comes in and plays a vital role as it is a clean source and has a very promising future in the global energy sector. Savonius turbine is a type of vertical axis wind turbine (VAWT) which is predominantly rotated by the drag force from the wind. It is self starting and can extract wind energy from low wind speeds and is very practical to install it in crowded places due to its compact geometry. This thesis is a review of the previous works presented by different authors. This project aims at discovering the influence of various design and performance parameters (aspect ratio, overlap ratio, tip speed ratio, blade shape, number of rotor blades and number of stages), turbulence models and turbine geometries on the performance of Savonius vertical axis wind turbine. A conventional Savonius vertical axis wind turbine (VAWT) with aspect ratio of 1, overlap ratio of 0.15 and TSR of 0.8 shows the maximum coefficient of power (C_P) The performance of conventional rotors can be enhanced by use of helical rotors; multi- staging and other modified blade geometries. Helical rotors with blade twist angle of 90^0 are better performing rotors than the conventional rotors. Modified Bach type rotor with a blade arc angle of 135^0, aspect ratio of 1.1, overlap ratio of 0.1 and at tip speed ratio (TSR)= 0.8 show the maximum coefficient of power (C_P) of 0.30. The results of numerical analyses were compared with that of the experimental data and it is found that for 2-D numerical analyses, realizable k-ε turbulence model shows better accuracy of estimation and for 3-D analyses, SST k- ω turbulence model shows better agreement with the experimental data.

Keywords:- *savonius wind turbine, wind energy, renewable energy, coefficient of power, tip speed ratio.*

I. INTRODUCTION

With every passing day, the demand for global energy production is increasing as the non- renewable energy resources are declining. As conventional energy resources like petroleum products contributes greatly to the issue of global warming and environmental pollution and this is where wind energy fits in as a suitable alternative for it. However, the problem arises with harvesting the wind energy and using it to produce power (electrical or mechanical). Wind turbines have proved to be a better option in harvesting the kinetic energy from the wind. Wind turbines can be classified into horizontal axis wind turbines and vertical axis wind turbines on the basis of their axes of rotation. There is an abundance of research works available on the HAWTs but the possibilities of the VAWTs are yet to be explored extensively. VAWTs are preferred over HAWTs due to its compact geometries, good starting characteristics and flexibility of operating in urban environments unlike the HAWTs. The VAWTs are sub- categorized into Savonius turbines and Darrieus turbines.

This work is an elaborative review on the Savonius VAWTs. It presents the influence of parameters related to the Savonius VAWTs on their performances. This review aims at studying the impact of design parameters such as aspect ratio, overlap ratio, endplate size ratio, types of rotors blades on the coefficient of power of the Savonius VAWTs. It also includes the effect of turbulence models (available on popular CFD codes), Reynolds number, wind speed and tip speed ratio on the performance of Savonius rotors. The possibilities of enhancing the performance by using different rotor blade geometries are also studied.

The first chapter provides the basic information about wind turbines, especially the vertical axis wind turbines. An elaborative description of Savonius turbines is presented including their working principle, advantages and disadvantages over the conventional horizontal axis wind turbines. The governing equations of the wind turbines are also discussed with proper derivations.

In the second chapter information related to the computational fluid dynamics and methods used for performing numerical analyses on CFD codes are presented. A brief discussion on the turbulence models is also carried out in this part.

The third and fourth chapters include the literature review on the Savonius turbines and the outcomes of the present study. In the third chapter, studies and analyses on Savonius rotors by various authors are reviewed precisely.

The fourth chapter includes the conclusions from the present study where the important outcomes are summarized.

II. CONTEXTUALISATION

A. Wind turbine

Wind turbine is an energy conversion device or rotating device used to extract kinetic energy of wind to generate mechanical or electrical power [18][24]. It rotates due to the difference in the air pressure between both the sides of its blades. This rotational motion can be used to produce mechanical work or rotate the shaft of a generator to produce electrical power. Wind turbines are classified into horizontal axis wind turbines and vertical axis wind turbines, based on their axis of their rotation [4][24]. The turbines whose axis of rotation is horizontal or parallel to the ground or almost parallel to the direction of the flow of wind are called Horizontal Axis Wind Turbines or HAWTs. On the other hand, Vertical Axis Wind Turbines or VAWTs are the ones whose axis of rotation is vertical and normal to the ground or almost normal to the direction of the flow of wind. There are two forces that are responsible for the rotation of the blades of the wind turbines, viz, lift force and the drag force from the wind. With all different shapes and types of wind turbines available, it becomes necessary to compare their efficiency. The aerodynamic efficiency of a wind turbine is described by the power coefficient of it and it is best explained by the Betz equations, which is described in the later part of the thesis. Power coefficient of a wind turbine is the amount of energy extracted by the turbine from the total available wind energy [21][24][25]. The HAWTs are widely used turbines in the global wind energy sector because of its advantage over VAWTs with regards to the efficiency and large scale power generation [4][22] [26]. However, there are a few significant advantages of VAWTs over HAWTs, because of which they are prioritized to use in the urban environments. These advantages are discussed in the next section of the thesis.

Further, the VAWTs are classified into Savonius type and the Darrieus type based on the design of their blades [4][6][22][26]. The Savonius wind turbine rotates predominantly by the drag force from the wind [3][4][5] and on the other hand, the Darrieus turbine rotates predominantly by the lift force [6][22]. The Darrieus turbine shows better aerodynamic performances than the Savonius turbine and is used to generate power in small scale [6][26]. However, at low wind speeds the Savonius turbine outperforms the Darrieus turbine [26].Moreover the Darrieus turbines have low reliability due to the large torque ripples and the cyclic stresses acting on the tower that holds its blades [18].

In today's era, wind turbines are primarily installed to lessen the burden of electricity production from the conventional power plants. The performance of every wind turbine can be described graphically by its power performance curve. It is the graphical illustration of the electrical power output as a function of the wind speed at the height of the turbine blades [24].

The curve has three distinctive spots, namely cut- in speed, rated speed and the cut- off speed. Cut- in speed is the minimum speed of wind at which useful power can be produced, whereas the maximum wind speed at which the turbine is designed to produce power is called the cut- off speed. Rated speed is typically the speed of the wind at which maximum power can be produced [24]. While designing a wind turbine, these parameters are quite necessary to keep in mind.

Advantages of VAWT over HAWT-

- VAWTs have compact geometries, so they can be easily installed, maintained and serviced timely. Also, because of their compact shape and geometries, they do not posses any threat to the surroundings in any accidental scenario [2][5][22],
- VAWTs have good starting characteristics. They are self staring devices and can start rotating at very low starting torques. So, unlike the HAWTs, they can be installed in places with lower wind speeds. Also, they have the ability to extract wind flowing from any direction [1][2][3][5][22],
- Unlike HAWTs, they don't require a supportive tower to hold the blades and the generator. The generator is mounted below the blades and placed on the ground.
- Moreover, the VAWTs are independent of the yaw mechanism and over speed control mechanisms [6][26],
- Due to lower noise level than the HWATs, the VAWTs are suitable for the urban environment [1][2][22],
- The VAWTs performs better under highly turbulent wind conditions [1][8].

B. Savonius wind turbine

The Savonius turbine was first introduced by a Finnish engineer named S.J. Savonius in the year 1922 [4][22][26]. A conventional Savonius wind turbine is a VAWT which has blades in the shape of semi cylindrical surfaces opposite to each other, attached by a shaft or two end plates or both. It resembles the shape of 'S' when viewed from the top [9,10]. Each blade has a concave and a convex side [4]. It rotates due to the pressure difference created on the concave and the convex sides of the blades by the drag force of the wind flow [3][8]. However, the lift force of the wind also contributes on a small scale to the rotation of the blades, which is quite insignificant and is not considered in its numerical studies [4]. Apart from electrical power generation, these turbines are used for pumping water, providing ventilation to houses and agitating water to keep ponds ice- free in the winters [26].

The C_P values of conventional Savonius VAWTs ranges from 0.1 to 0.25. It has high positive coefficients of static torque at certain angles but also generates negative coefficient of torque from angles 135^0 to 165^0 and 315^0 to 345^0 in a single cycle of 360^0 of rotation [8][19]. Positive coefficient of torque implies that the wind delivers torque to the turbine blades whereas having negative torque coefficient means the rotor blades are delivering torque to the wind. Due to the generation of the negative torque coefficient and high variation of static torque coefficients, the conventional Savonius turbine shows poor efficiencies in comparison to the HAWTs and the other VAWTs [2][6]. In order to counter this problem, researches have been done to alter the design of the conventional Savonius turbines. One such approach is the introduction of the helical shaped Savonius turbine, which performs better than the conventional one [18][19].

Moreover, it has also been observed that by increasing the number of stages of the turbine, the issue of negative torque generation can be tackled [19]. Researches related to the modification of the blade designs have also been done to obtain better performance of the Savonius turbine [4]. Also by the use of defectors and curtains the performance of a Savonius turbine can be increased significantly [2][4]. Few modifications of the blade design of the conventional Savonius wind turbines are shown in the figure below.

C. Betz equation and Betz limit

Betz equation is based on theories of conservation of mass and conservation of energy. It explains the conversion of kinetic energy of wind into rotational movement of the turbine and the power extracted from the flowing wind by the turbine. This equation applies to all the types of wind turbines. It was first introduced by a German engineer named Albert Betz through his book “Wind Energy and its Extraction from Wind Mills”, published in the year 1919.

Let us consider the velocities of wind before the rotor as V_1 and after the rotor as V_2, surface area of air mass before the rotor is A_1 and after the rotor is A_2 respectively. Let the velocity of wind at the rotor cross section be V and the surface area of the rotor cross section be A (figure 1).

Assumptions- (a) the rotor does not have any hub, (b) the rotor has infinite number of blade and it does not provide any drag resistance to the wind flowing through it.

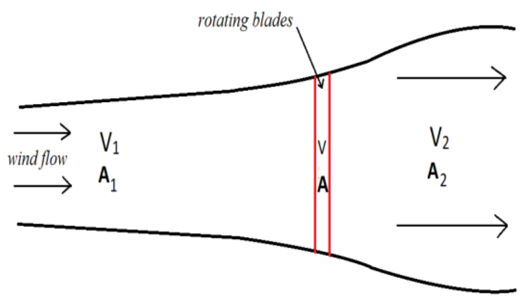

Fig. 1: Wind flow through swept area of a VAWT

$$\dot{m} = \rho A_1 V_1 = \rho A V = \rho A_2 V_2 \quad (1)$$

Therefore the mass flow rate of wind, $\dot{m} = \rho A_1 V_1 =$

Force on the rotor blades due to the wind,

$$F = m \quad (2)$$

$$F = m\frac{dV}{dt} \quad (3)$$

$$F = \dot{m} dV \quad (4)$$

$$F = \dot{m}(V_1 - V_2) \quad (5)$$

$$F = \rho AV(V_1 - V_2) \quad (6)$$

Incremental work done in the wind stream,

$$E = Fdx \quad (7)$$

Power content of the wind,

$$P = \frac{dE}{dt} = F\frac{dx}{dt} = FV = \rho AV^2(V_1 - V_2) \quad (8)$$

Power as a rate of change of kinetic energy of the wind,

$$P = \frac{\frac{1}{2}mV_1^2 - \frac{1}{2}mV_2^2}{\Delta t} \quad (9)$$

$$P = \frac{1}{2}\dot{m}(V_1^2 - V_2^2) \quad (10)$$

$$P = \frac{1}{2}\rho AV(V_1 - V_2)(V_1 + V_2) \quad (11)$$

Equating equation 1 and 2, we get

$$\rho AV^2(V_1 - V_2) = \frac{1}{2}\rho AV(V_1 + V_2)(V_1 - V_2) \quad (12)$$

$$V = \frac{1}{2}(V_1 + V_2) \quad (14)$$

Equation (14) implies that the wind speed at the rotor cross section is the average of the upwind and downwind speeds. Also the equation is invalid for the condition $V= 0$

Putting the value of V in the equation (8), we get,

$$P = \frac{1}{4}\rho A(V_1 + V_2)^2(V_1 - V_2) \quad (15)$$

$$P = \frac{1}{4}\rho A(V_1^2 - V_2^2)(V_1 + V_2) \quad (16)$$

Therefore, the coefficient of power can be calculated by,

$$C_P = \frac{\text{power extracted by the rotor}}{\text{total power of the wind stream}} = \frac{\frac{1}{4}\rho A(V_1^2 - V_2^2)(V_1 + V_2)}{\frac{1}{2}\rho AV_1^3} \quad (17)$$

The ratio of V_2 and V_1 can also be expressed as the interference ratio,

$$b = \frac{V_2}{V_1} \quad (18)$$

Therefore, force in terms of interference ratio can be expressed as,

$$F = \frac{1}{2}\rho AV_1^2(1 - b^2) \quad (19)$$

The extractable power P in terms of the interference factor b can be expressed as,

$$P = \frac{1}{4}\rho AV_1^3(1 - b^2)(1 + b) \quad (20)$$

Power coefficient in terms of b can be expressed as,

$$C_p = \frac{1}{2}(1 - b^2)(1 + b) \quad (21)$$

Differentiating the equation (21) w.r.t ‘b’, we get,

$$\frac{d(C_p)}{db} = \frac{1}{2}\frac{d}{db}[(1-b^2)(1+b)] = \frac{1}{2}(1-3b)(1+b) \tag{22}$$

Equating $\frac{dC_p}{db} = 0$, we get,

$$\frac{1}{2}(1-3b)(1+b) = 0 \tag{24}$$

$$b = \frac{1}{3} \tag{25}$$

$$\frac{V_2}{V_1} = \frac{1}{3} \tag{26}$$

This implies that for optimum operation of the wind turbine the downwind speed should be 1/3 of the upwind speed.

Therefore, optimum $C_{P,}$

$$C_{P_{opt}} = \frac{1}{2}\left[1-\left(\frac{1}{3}\right)^2\right]\left(1+\frac{1}{3}\right) \tag{27}$$

$C_{p(opt)}$= 59.26%

This is the maximum power that can be generated or called the Betz limit. It means that a wind turbine can extract at most 59.26% of kinetic energy from the flowing wind.

III. DESIGN AND PERFORMANCE PARAMETERS

Reynolds's number (Re) - Re is a non- dimensional number which is used to predict the nature of the flow. It is ratio of the inertia force to the viscous force of the fluid.

Aspect ratio- Aspect ratio is defined as it is a ratio of height and rotor diameter (H/D), while swept area (A), bearing friction, weight of rotor, wind velocity, keeping constant [1-4] [15].

Overlap ratio- Ratio of distance between the rotor blades to the diameter of the rotor (e/D) is called its overlap ratio [1-4][10-13] [15].

End plate size ratio - the ratio between the diameter of the endplates to the diameter of the rotor (D_0/D) is called endplate size ratio [11].

Swept area (A)- Swept area is the area swept by the rotor blades of a VAWT. It is calculated by the multiplying the diameter (D) and the height of the rotor (H) [23].

Cut- in speed- The speed of incoming wing at which a turbine starts to rotate on its own is called its cut- in speed [10]. The cut- in speed of turbines varies with the shape, size and geometry of the turbines. Ali et al. confirms through his study that the cut- in speed of both 2 and 3- bladed conventional Savonius turbine is between 2 to 3 m/s [10].

Tip Speed Ratio (TSR) – TSR is the ratio of the speed of the rotating blades to the speed of the incoming wind [1-5][23] [26].

$$\lambda = \frac{\text{tip speed of the rotor blade}}{\text{incoming wind speed}} = \frac{\omega D}{2V}$$

Torque coefficient (C_m) - C_m is the ratio of the pitching moment to the dynamic moment [1-4][26].

$$C_m = \frac{\text{pitching moment}}{\text{dynamic moment}} = \frac{T}{0.5\rho AV^2 r}$$

Power coefficient (C_P) – C_P is the ratio of the power generated by the turbine to the total power available in the wind [1- 4][26]. Mathematically it can be defined as,

$$C_p = \frac{\text{power generated by the turbine}}{\text{total power available in the wind}} = \frac{P_{out}}{0.5\rho AV^3} = C_m \text{x}\, \lambda$$

- Methods to enhance performance
  - Use of guided vanes,
  - Use of multi- staging,
  - Obstacle shielding of the returning blade of the rotor,
  - Use of curtain in front of the rotor,
  - Use of helical shaped rotor blades,
  - Use of 'V' shaped blades,
  - Use of conveyor deflector curtain,
  - Use of quarter blades,
  - Use of semicircular- elliptical combined blades.

IV. LITERATURE REVIEW

A. Wind channel

Bai et al. [1] performed extensive numerical analysis on the performance of Savonius wind turbine when it is placed in open space and inside wind channels of different widths (2D, 3D, 4D).

Cases	Description	V/V_D	C_p	C_p*	C_p/ C_p*
1	Open space	1	0.25	0.25	1
2	1D	1.10	0.57	0.24	3.1
3	2D	1.11	0.39	0.24	2.2
4	3D	1.10	0.34	0.24	1.9
C_p- Coefficient of power (in open space) C_p*- Coefficient of power (inside wind channel)					

Table 1: Comparison of performance parameters of Savonius turbine placed in open space and inside a wind channel of different widths [1]

The C_P of the turbine is the highest in a channel of width= 2D, if the pressure drop inside the channel is not considered. However, if the pressure drop inside the channel is considered, the CP of all the cases remains near about 0.25 but the power output of the turbine is highest in case 2 which is 3.1 times the power output of the turbine placed in open space.

Ahmed et al. [14] has performed numerical analysis on the performance of a helical Savonius VAWT inside a wind channel of 25D long and 10D wide. The rotor was placed at 5D from top and bottom, 5D upstream and 20D downstream to the centroid of the rotor.

Bai et al. [1] has studied the variation of C_P when the turbine is placed in open space and inside a wind channel at different locations. The turbine is placed inside a wind channel with its width equal to twice the diameter of the turbine, two scenarios are considered: the wind turbine is offset upward 0.5D from the centerline of the channel (Case 3A) and the turbine is offset downward 0.5D from the centerline of the channel (Case 3B). In Case 3A, the returning blade of the wind turbine is close to the channel wall with the center of the wind turbine located at 1D away from the channel wall while, in Case 3B, the advancing blade of the wind turbine is close to the channel wall with the center of the turbine 1D away from the channel wall. Table 2 lists the corresponding power coefficients and power generation in these two cases, with a comparison to that of the wind turbine in open space (Case 1) as well as that of the wind turbine located in the centerline of the channel (Case 3). The third column refers to the ratio to the wind velocity inside the tunnel to that of the wind velocity inside the wind channels. The 4th, 5th and the 6th column refers to the CP without considering the pressure drop inside the wind channel, CP after considering the pressure drop inside the wind channel and the power output of the turbine respectively. It is evident that the power coefficient and the power output is the highest in the model with the advancing blade near to the channel wall [1].

	Channel width	U_D/U_0	C_p	C_p*	P_{out}/P^*_{out}
Case 1	Open space	1.00	0.25	0.25	1
Case 3	3D	1.11	0.39	0.24	2.2
Case 3A	3D	1.07	0.36	0.22	1.8
Case 3B	3D	1.07	0.43	0.26	2.2

Table 2: Power coefficients and power generation of a Savonius-type VAWT at different locations in a long channel. TSR= 0.8 [1]

B. *Tip speed ratio*

Micha et al. [11] through his study proves that initially the coefficient of power increases and then decreases with increasing TSR values. However, the optimum TSR was found to be 0.8.

It is evident from the study conducted by Bai et al. that the optimum TSR for Savonius type VAWT is in the range between 0.7 to 1 [1]

Ferrari et al. [7] has studied the influence of TSR on the performance of a 2- bladed conventional Savonius turbine (figure 4.1.). SST k-ω turbulence model was used for analyzing the performance of both 2-D and 3-D models of the VAWT. The TSR values chosen for inspection were 0.58, 0.81 and 1.01 [7]. For the 3-D model, the power coefficient is the highest at TSR= 0.81 and for the 2-D model, it is the highest at TSR= 1.01 [7]. However, experimental results suggest that the power coefficient is maximum at TSR values around 0.8. So, in this case the 2-D model shows an overestimated result.

C. *Turbulance model*

Frikha et al. [3] has studied the influence of the standard k- ε and the RNG k- ε turbulence models on the performance of a conventional Savonius turbine. The standard k- ε model obtains a static torque coefficient of 0.34 which is closer to that of the experimental result of 0.34. The RNG k- ε turbulence model generated a static torque coefficient of 0.38.

A comparative study of 2-D SST k–ω, 3D SST k–ω, and Hybrid Detached-Eddy Simulation (DES) SST k–ω turbulence model was carried out to analyze the flow filed behavior r and wake geometry of a two bladed Savonius rotor [26]. It is perceived that 2-D SST k–ω turbulence model was over predicting, whereas 3-D SST k–ω turbulence model was slightly under-predicting the experimental results. The hybrid 3D DES/ k– ω SST turbulence model, on the other hand, gave a more accurate prediction [26].

In a study using RNG k–ε turbulence model, it is observed that 2-D simulation has over predicted the rotor performance, whereas 3-D simulation has shown more accurate predictions [26].

Hassan et al. [4] has made an extensive study on the influence of turbulence models on the performance of a two bladed conventional Savonius turbine. Numerical analysis was conducted on a 2-D model and a comparison was made between the C_P values obtained by using realizable k- ε, standard k- ε, RNG k- ε and the SST k- ω turbulence models with experimental results. It is found that the C_P values obtained by using the realizable k- ε model are the closest to the experimental C_P values. Moreover, the C_P values obtained by standard k- ε are also in good agreement with the experimental results. However, the results of the RNG k- ε and SST k- ω are far away from the experimental results with an average error of 47.5% and 55.4% respectively [4]. It can be observed from table 3, the values of C_P obtained by using Realizable k- ε turbulence model and physical experiment. The result from the numerical analysis doesn't have error more than ±5% from the experimental analysis. In the numerical analysis done by Realizable k- ε model, maximum coefficient of power is obtained at TSR=0.9 and on the contrary, the maximum CP obtained by physical experiment is obtained at TSR= 0.8 [4].

λ	k- ε (realizable)	Experimental	Error (%)
0.6	0.1446	0.1399	3.43
0.7	0.1536	0.1476	4.07
0.8	0.1513	0.1506	0.33
0.9	0.1562	0.1416	-0.70
1	0.1307	0.1320	-1.67

Table 3: Comparison of CP obtained by 2-D analysis (Realizable k- ε turbulence model) of a Savonius VAWT with experimental results done by Hassan et al. [4]

A comparison study was done between the coefficient of power obtained by the experimental and numerical analyses of a conventional Savonius turbine by Mirashi and Kumarappa [9]. The table… and figure… represents the data and the comparison of the analyses. It is evident from both table 4.4., and figure 4.6., that the RNG k- ε turbulence model shows good agreement of C_P and power output with the experimental analysis. The maximum value of C_P is obtained at wind speed of 6.5 (TSR= 0.92) in both numerical and experimental study. However, the maximum C_P obtained by numerical study is 0.167, which merely underestimates the C_P= 0.159 obtained by the numerical analysis [9]. Moreover, the C_P increases with the increasing wind in both the analyses [9].

V (m/s)	Power (W)		C_p	
	Experimental	CFD	Experimental	CFD
2.2	0.087	0.0917	0.093	0.098
3.7	0.527	0.549	0.118	0.122
4.9	1.442	1.508	0.139	0.145
6.5	3.85	4.034	0.159	0.167

Table 4: Comparison of power output and Cp obtained by experimental analysis and numerical analysis (RNG k- ε turbulence model) by Mirashi and Kumarappa [9]

Another numerical analysis was carried out on a 3-D model of a helical Savonius VAWT by Damak et al [4]. The analysis was performed by incorporating the finite volume method (FDM) and using the SST k-ω turbulence model. The result of the numerical analysis is in good agreement with experimental data with a maximum deviation of 2%.

Ferrari et al. [7] has tested the performance of a 2-D and a 3-D model of a conventional Savonius turbine using the SST k- ω turbulence model and compared it with the experimental results of C_P. The 2-D model overestimates the experimental value of C_P reporting a maximum efficiency at TSR= 1, 20% higher than experimental value. However, the results of 3D model are in good agreement with experiments with a peak of 0.202 at TSR 0.8 for a rotor with aspect ratio 1.1.

El- Askary et al. [17] have performed analyses on the relevance of different turbulence models on the performance of a 3-D Savonius VAWT model (figure 4.8.). Through his analyses he has found that the C_P value gained by using the RNG k-ε turbulence is the closest to the experimental C_P obtained by Fijisawa et al.

Ahmed et al. [14] has compared the performance results of helical rotor (3D model) obtained by using RNG k-ε, standard k-ε, realizable k-ε and the SST k-ω turbulence models with the experimental results of Fujisawa [14]. The torque coefficient obtained by the SST k-ω model is the closest to the experimental torque coefficient.

D. Overlap ratio and aspect ratio

Extensive studies have been done so far to know the effect of the overlap ratio of a turbine blade on its performance. The overlap ratio is a major parameter that influences the structure of the flow inside the rotor and consequently its aerodynamic performances, the influence of the overlap ratio has been widely investigated, and however there is not an accord among the outcomes acquired in previous studies [8]. Blackwell concludes that the optimum range of overlap ratio of a Savonius VAWT is 0.1 to 0.15 [8]. The study of Akwa et al. is also in good agreement with Blackwell's conclusion, which is a turbine with an overlap ratio of 0.15 shows, the best performance [8]. Bhowmick and Gupta have also confirmed through their study on VAWTS that the optimum overlap ratio of a Savonius VAWT is 0.147 [11].

Ahmed et al. [14] has performed a numerical analysis on helical rotors to find the best overlap ratio that shows the highest coefficient of torque and coefficient of power. In this literature, the author has used 5 different overlap ratios, viz. 0, 0.1, 0.15, 0.2 and 0.3 and kept the wind speed at 6 m/s. As seen in the figure 4.10., the torque and power coefficients significantly decrease as the overlap ratio increases from 0 to 0.3. At an overlap ratio of zero, the values of Cm and CP are 0.38 and 0.223, respectively. Here, it is worth mentioning that for the conventional rotor ($\varphi = 0°$), the highest values of Cm and CP were observed at δ = 0.15–0.2. Moreover, the highest coefficient of torque and coefficient of power is predicted at TSR values of 0.4 and 0.8 respectively for all overlap ratios.

Alit et al. [5] has made an extensive experimental analysis on the effect of overlap ratio, blade shape factor and blade arc angle on the performance of a Bach type VAWT. Where, overlap ratio= m/ D, blade shape factor= p/q and blade arc angle= Ψ. In the first analysis, the effect of overlap ratios of 0, 0.05 and 0.1 is studied by considering the blade shape factor as 0.5 and the blade arc angle as 900. In the 2nd analysis the effect of blade shape factors of 0.2, 0.5 and 1 is studied by considering overlap ratio of 0.0 and blade arc angle of 900. In the 3rd analysis the effect of blade arc angles of 900, 1100 and 1300 is studied by considering overlap ratio of 0 and blade shape factor of 0.5. The turbine with overlap ratio of 0 shows better coefficient of power values as compared to those of the overlap values 0.05 and 0.1. Blade shape factor of 0.05 has a slightly better power coefficient values than the other two blade shape factors. However, from the 3rd analysis, it is found that all three blade arc angles (900,1100, 1300) show similar power coefficient below TRS value of 0.4 whereas, the turbine with the blade arc angle of 1100 shows higher power coefficient value above the TSR value of 0.4. Also, all the turbines obtain higher values of power coefficient in the TSR range of 0.7 to 0.8.

Morshed et al. [6] has studied the effect of overlap ratio on a three bladed conventional Savonius turbine. Three designs with overlap ratios of 0, 0.12 and 0.26 are analyzed both numerically and experimentally. For the numerical analysis, mesh is generated using the software Gambit and the simulations are performed in Ansys Fluent using the standard k-ε turbulence model [6]. The turbine with the lowest overlap ratio (0) has the shown the highest torque coefficient and the turbine with the highest overlap ratio (0.26) have shown the lowest torque coefficient. Also, it is observed that the C_m values increase with the increase in Reynolds number [6][7].

Also, an analysis was done on the effect of aspect ratio of the rotor by Ferrari et al. [7] and it is found that the value of C_p increases with the increase in aspect ratio and has a maximum value of (0.205) at an aspect ratio of 1.644.

ISSN No:-2456-2165

Dhoble and Mahalle claims that the aspect ratio of a Savonius VAWT is a function of its performance [16]. While keeping high aspect ratio gives better coefficient of performance due to effects of tips of bucket. In many of studies shows that aspect ratio should not be less 2 which give best results [16].

E. Plate size ratio

Ahmed et al. [14] has studied the effect of the end plate size ratio (D_0/D) on the performance of a helical Savonius VAWT. The authors have compared the estimated C_m and C_P for all the tested end plate size ratios (0, 0.5, 1, 1.1, and 1.2). It is found that using endplates significantly increases the power coefficient of the helical Savonius rotor. Based on the figures the torque coefficient increases with an increase in the endplates size ratio from zero to 1.1. With a further increase beyond 1.1, a reduction of both torque and power coefficient is observed. The reason is likely due to the endplates preventing the escape of air from the tips of the concave side of both the advancing and returning blades to the external domain. This keeps the pressure difference between the concave and convex side of the blades at high levels over the height of the turbine. Moreover, the Cm and the CP attain their highest values at TSR= 0.4 and TSR= 0.8 respectively.

Micha et al. [11] has studied the performances of helical Savonius turbines with end plates and without endplates. Helical rotors are used to counter the negative torque generation but has demerit of compromising on the maximum torque produced by the turbine. Through his work, the author claims that the performance of the helical rotor with end plates outperforms that without end plates. The maximum torque obtained by the rotor with endplates is 0.314 Nm whereas in case of the rotor without end plates, it is slightly lower which is 0.310 Nm.

F. Turbine blade shape and configuration qnd turbine stage

Saha and Thotla [8] have concluded that a Savonius turbine has optimum performance if the rotor has a two bladed configuration, irrespective of the number of stages of the turbine [8]. Ali et al. have also studied the trend of the power coefficient with respect to increasing TRS in both two and three blades Savonius turbines. The knowledge gained from his study is that the value of CP increases till TSR is around 0.8 and then it starts to decline, in both the 2- and 3-bladed rotors. However, the 2- bladed rotor shows higher value of CP than the 3- bladed rotor for same TSR values [8].

Ali et al. [10] has studied the performances of two and three bladed conventional Savonius VAWTs at low wind speeds and made a comparison. The analysis was done by performing physical experiments with models of both the turbines in a wind tunnel. Results show high torque generation at lower TSR values for both the 2- bladed and 3-bladed rotors. However, the 2- bladed rotors show higher value of C_m than that of the 3- bladed rotor for all TSR values. The reason is that increasing the number of blades will increase the drag surfaces against the wind air flow and causes to increase the reverse torque that leads to decrease the net torque working on the blades of Savonius wind turbine. Moreover, the power coefficient of both the rotors are highest at TSR= 0.8 and the 2- bladed rotor shows higher power coefficient than the 3- bladed turbines at all values of TSR.

Mirashi and Kumarappa [9] have used a splitter geometrical arrangement on the blades of a conventional Savonius turbine with guided vanes to study its performance and make a comparison with a conventional Savonius VAWT. The numerical analysis was performed on 3-D models using Ansys Fluent 14.5 CFD software using the RNG k- ε turbulence model. Both the models of VAWT were studied under the influence of different wind speeds (V= 2.2, 3.7, 4.9, 6.5 m/s) corresponding to their TSR values (0.84, 0.68, 0.83, 0.92). The power coefficient of both the turbines increases with increasing wind speed. However the rotor with splitter blades has higher C_P and slightly better power output than the conventional rotor. At 6.5 m/s wind speed, the rotor with splitter blades shows a C_P of 0.177 and the conventional rotor shows a C_P of 0.1665. Also in terms of the power output, the rotor with splitter blades slightly performs better than the conventional one.

There was also a comparison made between the values of C_p obtained by a conventional rotor having splitter blades with guided vanes and without guided vanes. C_p of the rotor with guided vanes show better performances than the rotor without guided vanes for all the wind speeds. However, the maximum C_p for the rotor with guided vanes is 0.208 which is obtained at a wind speed of 6.5 m/s corresponding to a TSR value of 0.92 whereas its counterpart has a C_p of 0.177 at the same wind speed and TSR [9].

Kothe et al. [13] has done an extensive numerical analysis on a single stage helical Savonius turbine with twist angle of 180^0 and a 2- stage conventional Savonius turbine and compared their performances with the experimental results. The simulations were performed using the SST k- ω turbulence model in the Ansys Fluent CFD code and the mesh refinement of this work is accomplished by the GCI method (Grid Convergence Index).

At TSR= 0.2 the 2- stage conventional Savonius VAWT shows higher torque coefficient than the helical Savonius VAWT. However, at higher TSR values (TSR= 0.5, 0.7 and 0.8) the helical rotor outperforms the conventional 2- stage rotor in terms of the torque coefficient. At TSR= 1, i.e., when the tip speed of the rotor blade is equal to incoming wind velocity, both the rotors show somewhat same torque characters [13]. A similar kind of trend is shown by the power coefficient comparison. At lower TSR values the conventional 2- stage rotor performs better than the helical rotor, whereas at higher TSR values the helical rotor outperforms the conventional 2- stage rotor [13].

Saha and Rajkumar [2] compared the performances of helical rotors experimentally with twist angle of 10^0, 12.5^0 and 15^0 and a conventional rotor (0^0). It is observed that all the helical rotors outperform the conventional Savonius rotor in terms of coefficient of power. Moreover, the rotor with a 15^0 angle of twist performs better at low wind speeds and the rotor. Also, all the rotors show their maximum C_P at TSR= 0.65.

Ahmed et al. [14] studied the helical shaped Savonius turbines (with end plates) of different overlap ratios, twist angles and circular end plate size ratios to find the best combination of these design parameters. The SST k- ω turbulence model was used to perform the numerical analysis of these models. Firstly, 10 models of the helical rotor were estimated by combination of all the twist angles and two overlap ratios (0 and 0.15) for their C_P and C_m values (table 5).

Twist angles	Overlap ratios
0^0	0
45^0	0.1
90^0	0.15
135^0	0.2
180^0	0.3

At wind speed of 6 m/s, the coefficient of torque obtained by all the models having different angle of twist has been compared. It is found that the helical rotor having the twist angle of 45^0 irrespective of the overlap ratio shows the highest coefficient of torque and coefficient of power at all TSR values. For $\delta = 0.15$, the maximum torque coefficient is observed at $\lambda = 0.4$ for all twist angels except 90° where the maximum torque coefficient occurs at $\lambda = 0.3$. In addition, the maximum torque coefficient is found to be 0.33 at a twist angle of 45° while the minimum value is observed at a twist angle of 180°. Moreover, all the 10 models show the highest C_P value at TSR= 0.8. Results show that at any value of tip speed ratio (λ), the C_m increases with an increase in twist angle up to an optimum value of $\varphi = 45°$ then gradually decreases till $\varphi = 180°$. The twist angle $\varphi = 45°$ causes the blade to consistently face the oncoming flow. This result in increasing the positive torque generated over a complete cycle. The coefficient of torque generated by the entire models do not have any negative value at any rotation angle, so there is no negative coefficient of torque generated [14].

El- Askary et al. [17] have made an extensive study on performances of conventional, helical and a new modified helical Savonius VAWT and compared them. All the helical rotors designed have twist angle of 45^0, aspect ratio of 1 and overlap ratio of 0.15. For all the 3-D models numerical analyses was done by using the RNG k- ε turbulence model in Ansys Fluent CFD code. All the helical models outperform the conventional Savonius VAWT. Also, the conventional Savonius VAWT is the worst performing rotor. Moreover, all the models show the highest value of C_P at TSR= 0.8 and C_m at TSR= 0.4. The helical rotors do not show any negative toque coefficient at any rotor angle. The modified helical rotor with twist is found to attain the highest C_P of 0.22, as compared to 0.174 for the conventional rotor, with a performance gain of 26.4%.

Kamoji et al. [19] have performed analyses on the performance of helical Savonius VAWT (aspect ratio= 0.88; overlap ratio= 0 and aspect ratio= 0.96 and overlap ratio 0.1) and a conventional Savonius VAWT (aspect ratio= 1 and overlap ratio= 0.15). The RNG k- ε turbulence model was incorporated to perform the analyses in the Ansys Fluent CFD code. The conventional Savonius VAWT has the highest C_P and C_m and outperforms all the helical rotors for both the Reynolds number of 120000 and 150000. The conventional rotor shows C_P of 0.18 at TSR= 0.76 and Re= 150000, whereas the best performing helical rotor has a C_P of 0.17 at TSR= 0.65 and Re= 150000. Also, at Re= 120000 the conventional rotor has higher values of Cm than the helical rotors at all TSR values. However, at Re= 150000, the helical rotor with aspect ratio= 0.88 and overlap ratio= 0 show higher values of C_m than the other two models at lower values of TSR, but at higher values of TSR the conventional rotor again outperforms the helical rotors.

Another analysis was performed by Kamoji et al. [19] to compare the performances of helical rotors with central shaft and without central shaft. It is found that the rotor without central shaft and an overlap ratio of 0 outperforms the rotor with central shafts having overlap ratios of 0 and rotors without central shafts but with overlap ratios of 0.1 and 0.16 respectively.

Roy and Saha [15] have compared the performances of conventional Savonius, semi- elliptical, Benesh type, modified Bach type and a new model of Savonius VAWT designed by them. The new model is designed by considering the design parameters of the Benesh type and the modified Bach type VAWTs. The analyses were performed using physical models inside a test rig. Performances of all the 5 models were compared with respect to the changing TSR values and the tests were performed for five different Reynolds numbers (60000, 83000, 98000, 120000 and 150000). It was observed that the torque coefficient values decrease with the increase of TSR. This was mainly caused by the gradual loads applied to the turbine shaft, which in turn, reduces the turbine rotational speed. On the other hand, the power coefficient increases with an increase of TSR up to a certain maximum value, beyond which it decreases with further increase in TSR. The newly developed blade gives a C_{Pmax} of 0.27 at TSR = 0.77. At this low Reynolds number (Re = 60000), the modified Bach type has shown a nearly similar performance to the newly developed Savonius VAWT; whereas, the conventional semicircular blade has displayed the lowest power and torque coefficients. The performance gains of the newly developed SSWT over conventional, semi-elliptic and Benesh type turbines are found to be 28.6%, 17.4% and 3.8%, respectively. All the model shows maximum value of C_P at Re= 120000. In all the cases, the newly developed 2- bladed turbine shows an improvement in the power and torque coefficients as compared to other tested turbines. A C_{Pmax} of 0.31 is obtained for the newly developed turbine at Re = 120000 and TSR = 0.82 [15].

Roy and Saha [26] states that multi-staging is usually done to improve the self-starting capability of a Savonius rotor. It is found from their study on the effect multistage of VAWT is that multi-staging increases the starting torque of the rotor [26].

Dhoble and Mahalle [16] through their review analysis claims that two stage rotor has best performance than single stage Savonius rotor. Also, for multistage rotors the angle between the rotor blade in the stages 45^0 and 90^0 shows better performances than other angles.

G. Reynolds number

Morshed et al. [6] found that at higher Reynolds number the turbine without overlap ratio gives better aerodynamic coefficient, and at lower Reynolds number the model with overlap ratio gives better result.

Roy and Saha [15] have studied the effect of Reynolds number on the maximum coefficient of power. It is observed that the maximum coefficient of power of all the turbines increases from Re= 60000 to Re= 120000 and then starts to decline till Re= 150000.

It is clearly evident from the study conducted by Kamoji et al. [19] that both C_P and C_m of the rotor increase with the increasing Reynolds number. The turbine running at wind speed of 14 m/s corresponding to Re= 201958 shows the highest CP and Cm at TSR range of 0.65 to 0.75 and 0.5 to 0.6 respectively.

ACKNOWLEDGMENT

This work is an outcome of the constant support from the Department of Mechanics and Systems, Polytech Tours, University of Tours. Moreover, the assistance provided by Gaelle Berton (Assistant professor), with her knowledge on the subject was very valuable in commencing the work.

REFERENCES

[1.] Bai, H. L., Chan, C. M., Zhu, X. M., & Li, K. M. (2019). A numerical study on the performance of a Savonius-type vertical-axis wind turbine in a confined long channel. Renewable Energy, 139, 102–109. doi:10.1016/j.renene.2019.02.044.

[2.] Saha, U. K., & Rajkumar, M. J. (2006). On the performance analysis of Savonius rotor with twisted blades. Renewable Energy, 31(11), 1776–1788. doi:10.1016/j.renene.2005.08.030.

[3.] Frikha, S., Driss, Z., Kchaou, H. & Abid, M. S. (2015) Effect of the turbulence model on the aerodynamic structure around a Savonius wind rotor, 22ème Congrès Français de Mécanique.

[4.] Hassan Saeed, H. A., Nagib Elmekawy, A. M., & Kassab, S. Z. (2019). *Numerical study of improving Savonius turbine power coefficient by various blade shapes. Alexandria Engineering Journal.* doi:10.1016/j.aej.2019.03.005.

[5.] Alit, I. B., Andyani, I. A. S. & Mirmanto. (2018) Effect of Overlapping Ratio, Blade Shape Factor, and Blade Arc Angle to modified Rotor Savonius performances, International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 1 (2018) pp. 411-416 © Research India Publications. http://www.ripublication.com

[6.] Morshed, K. N., (2010) Experimental and Numerical Investigations on Aerodynamic Characteristics of Savonius Wind Turbine with Various Overlap Ratios, Electronic Theses and Dissertations. 773. https://digitalcommons.georgiasouthern.edu/etd/773

[7.] Ferrari G, Federici D, Schito P, Inzoli F, Mereu R, CFD study of Savonius wind turbine: 3D model validation and parametric analysis, *Renewable Energy* (2017), doi: 10.1016/j.renene.2016.12.077.

[8.] Zemamou, M., Aggour, M., & Toumi, A. (2017). Review of savonius wind turbine design and performance. Energy Procedia, 141, 383–388. doi:10.1016/j.egypro.2017.11.047.

[9.] Mirashi, D. N., Kumarappa, S. (2016) CFD Analysis on Two Bladed Savonius Wind Turbine With and Without Splitter, International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056 Volume: 03 Issue: 11 www.irjet.net p-ISSN: 2395-0072 ©

[10.] Ali, M. H., (2013) Experimental Comparison Study for Savonius Wind Turbine of Two & Three Blades At Low Wind Speed, International Journal of Modern Engineering Research (IJMER) www.ijmer.com Vol. 3, Issue. 5, Sep - Oct. 2013 pp-2978-2986 ISSN: 2249-6645

[11.] T. Micha Premkumar, Seralathan Sivamani, E. Kirthees, V.Hariram and T. Mohan, Data Set on the Experimental Investigations of a Helical Savonius Style VAWT With and Without End Plates, *Data in Brief*, https://doi.org/10.1016/j.dib.2018.06.113

[12.] Kassem, Y,Çamur H,Bahroun A. A., Abughnida O. A. M & Alghazali, A. (2018) Performance investigation of Savonius Turbine with New Blade Shape: Experimental and Numerical study, International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 10 (2018) pp. 8546-8560 © Research India Publications. http://www.ripublication.com

[13.] Kothe LB, Möller SéViç, Petry AP, Numerical and experimental study of ahelical Savonius wind turbine and a comparison with a two-stage Savonius turbine, *Renewable Energy* (2019), doi: https://doi.org/10.1016/j.renene.2019.10.151.

[14.] Saad, A. S., El-Sharkawy, I. I., Ookawara, S., & Ahmed, M. (2020). *Performance enhancement of twisted-bladed Savonius vertical axis wind turbines. Energy Conversion and Management, 209, 112673.* doi:10.1016/j.enconman.2020.112673

[15.] Roy, S., & Saha, U. K. (2015). *Wind tunnel experiments of a newly developed two-bladed Savonius-style wind turbine. Applied Energy, 137, 117–125.* doi:10.1016/j.apenergy.2014.10.022

[16.] Dhoble, L. N. & Mahalle A. K., CFD analysis of Savonius vertical axis wind turbine: A review, International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056 Volume: 03 Issue: 01 | Jan-2016 www.irjet.net p-ISSN: 2395-0072

[17.] Saad, A. S., Salam, A. M. A.,, Sakr, I. M. & El-Askary, W. A. Performance Analysis of a Helical Savonius Wind Turbine with Modified Rotor, 17th International Conference on *AEROSPACE SCIENCES & AVIATION TECHNOLOGY, ASAT - 17* – April 11 - 13, 2017

[18.] Duffett , I., Perry J., Stockwood B. & Wiseman J. (2009), Design and evaluation of twisted Savonius wind turbine, vertical wind energy engineering

[19.] Kamoji, M. A., Kedare, S. B., & Prabhu, S. V. (2009). Performance tests on helical Savonius rotors.

Renewable Energy, 34(3), 521–529. doi:10.1016/j.renene.2008.06.002

[20.] S. Jagadish Venkata Sai, T. Venkateswara Rao, Design and Analysis of Vertical Axis Savonius Wind Turbine, International Journal of Engineering and Technology (IJET), e-ISSN : 0975-4024

[21.] Magdi Ragheb and Adam M. Ragheb, Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio

[22.] Ragheb, M.(2015), book: Vertical axis wind turbines

[23.] Whittlesey, R. (2017). *Vertical Axis Wind Turbines. Wind Energy Engineering, 185–202.* doi:10.1016/b978-0-12-809451-8.00010-2

[24.] Zhao, D., Han, N., Goh, E., Cater, J., & Reinecke, A. (2019). *General introduction to wind turbines. Wind Turbines and Aerodynamics Energy Harvesters, 1–20.* doi:10.1016/b978-0-12-817135-6.00001-6

[25.] Kalmikov, A. (2017). *Wind Power Fundamentals. Wind Energy Engineering, 17–24.* doi:10.1016/b978-0-12-809451-8.00002-3

[26.] Roy, S., & Saha, U. K. (2013). *Review on the numerical investigations into the design and development of Savonius wind rotors. Renewable and Sustainable Energy Reviews, 24, 73–83.* doi:10.1016/j.rser.2013.03.060

[27.] Previtero, C. (2018), Computational Fluid Dynamics analysis and Experimental Tests of a Small Vertical Axis Wind Turbine: Choice of Design, École Polytechnique I'Université de Tours.