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Three-Dimensional CFD Analysis on Modified Savonius Wind Turbine

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Abstract - *The Savonius wind turbine is the simple type of vertical axis wind turbine (VAWT). It is well known for it's simple design consisting of 2 or 3 arc-shaped blades. Despite the simple design it's low power coefficient (Cp) attracts researches to increase it's aerodynamic performance. Three-Dimensional numerical simulations have been performed on the modified Savonius wind turbine with novel blade design, in order to increase the power coefficient and overall performance. All the simulations performed are based on k-ω SST turbulence model and has been performed in ANSYS Fluent. The average power coefficient is found at different tip speed ratios of the turbine and has been validated with experimental data.*

***Key Words*: Vertical Axis Wind Turbines, Savonius Wind Turbine, 3D CFD**

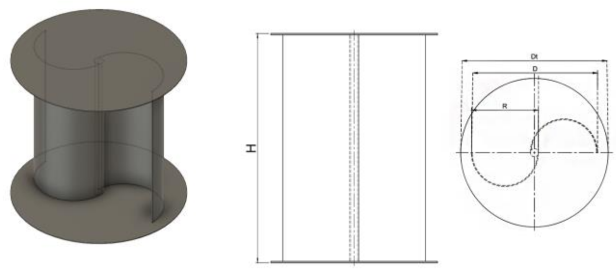
1. INTRODUCTION

Energy plays a vital role for any country's economic growth. Large amount of energy resources are consumed to meet the ever increasing life standard of citizens. Meeting the energy requirements through conventional energy resources such as coal, fossil fuels etc. has it's own disadvantages. The extensive use of coal and gas will have adverse effect on the environment and may ultimately lead to depletion of fossil fuels. This serves the necessity to shift to the renewable energy resources such as solar, wind and tidal Energy. Wind energy is the cleanest and abundantly available among all the renewable energy resources. Wind energy has been the fastest growing renewable energy sector in India. As of February 2021 the total installed wind power capacity was 38.789 GW and is 4th largest installed wind power capacity in the world. Wind energy is converted into useful electric energy with the help of Wind energy conversion systems (WECS). These are broadly divided into two types horizontal axis wind turbine (HAWT) which are widely used due to high power generation. And Vertical axis wind turbines (VAWT), unlike HAWT these are simple and does not require any special mechanism for pitch and yaw motion. Savonius wind turbine is the one of the commonly used vertical axis wind turbine, The simple design and relatively low power coefficient displays a room for improvement and gives an opportunity to optimize the performance. It is a drag type wind turbine, most of the power is extracted from the drag and lateral forces acting on the turbine. Savonius type W.T widely used in low wind speed and for decentralized power generation. Several researchers worked to enhance the performance of savonius wind turbine by changing the structure of the turbine, Konrad Kacprzak *et al*. [6] studied the performance of batch-type and spline-type blades and found out that there is 16% increase in efficiency for spline-type.

2. METHODOLOGY

The analysis mainly concentrated on increasing the power coefficient of classical single stage two blade savonius wind turbine. A spline shaped blade profile with internal scoops has been considered and a Three-Dimensional CFD analysis will be performed on classical and modified savonius wind turbine and will be validated with the existing experimental data. The analysis is carried out at different tip speed ratios and the free wind velocity of 7 m/s, turbine diameter(D) and with zero overlap ratio are considered same as in blackwell *et al*. [5] experimental data.

2.1 Conventional Savonius Geometry



(a) (b)

Fig -1: (a) Conventional Savonius Wind Turbine (CSWT) model, (b) Schematic Diagram of CSWT as per the experimented model [5].

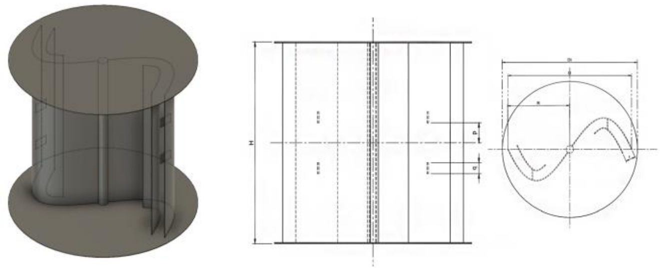
As shown in the figure the classical savonius turbine is composed of two semi-circular blades with a diameter(D), height(H) and a shaft of diameter(O). The two circular end plates are also considered with diameter(Dt). The ratio between the turbine and the end plate diameter is 1.1 and taken as per the literature review [8] it has an aspect ratio 1. Zero overlap ratio is considered for the turbine as per the experimental model in [5] and a Thickness of 2.5 mm is considered during the modeling of the CSWT.

Table -1: Geometry parameters of CSWT model

Total height of the rotor (H)	1 m
Nominal Radius (R)	0.47 m
Diameter of the rotor (D)	0.94 m
Thickness of turbine (t)	0.0025 m
End plates Diameter (D_t)	1.1 m
Overlap Ratio	0
Aspect Ratio	1

2.2 Modified Savonius Geometry

In order to increase the overall performance of the classical savonius wind turbine, novel spline shaped blade profile with internal scoops has be considered. The scooplets for the turbine are same shape as the spline curve which are offset at distance of 'r' from the main blade. The scoops are attached to the main blade with the help of two support structures which are located at distance of 'p' from the center line. All other parameters such as diameter(D), height(H), overlap ratio and aspect ratio are same as the CSWT.



(a) (b)

Fig -2: (a) modified spline-type savonius wind turbine (b) Schematic diagram of new spline-type savonius wind turbine.

Table -2: Geometry parameters of new spline-type savonius wind turbine model

Total height of the rotor (H)	1 m
Diameter of the rotor (D)	0.96 m
Nominal Radius (R)	0.48 m
End plates Diameter (D_t)	1.1 m
Scooplet offset (r)	0.06 m
Overlap ratio	0
Aspect ratio	1

3. CFD Analysis

The analysis has been performed using the fluent software which is one of the commercial CFD tool by ANSYS. The numerical domain and meshes were generated using fluent meshing. The k-ω SST turbulence model has been implemented in the current research because this turbulence model has shown robustness in so many applications from turbo machines to solar plant concept analysis. It is the most commonly used model in previous VAWT CFD studies on both savonius wind turbine and darrieus wind turbine. This model is preferred due to the faster convergence when compared to 4-equation transition SST turbulence model. Transient simulation is considered and the parameters such as torque, lift and drag are calculated for a total of 4 revolutions.

3.1 Computational domain generation

The experimental test of wind turbines will be performed in a wind tunnel. However methods exists for purely numerical studies using computation fluid dynamics simulations. These CFD simulations are sensitive to the domain size of the fluid/solid meshes. The air flow and it's complexity will be calculated by the software based on the input turbulence model.

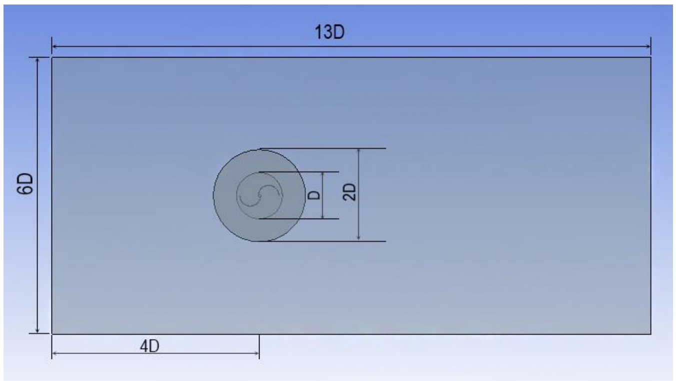


Fig -3: Domain generation for CFD analysis

The domain generation is a pre-processing step in a CFD analysis, which is the most important step. The savonius wind turbine is subjected to the external flow. The flow domain will be enclosed in a cuboid which consists of inlet & outlet for fluid flow and for the lateral faces of the domain, symmetry boundary condition has been assigned. The savonius wind turbine of diameter(D) is placed at a distance of 4D from the inlet and 9D away from the outlet in order to capture the wake generated behind the turbine. The three-dimensional computational domain consists of two domains, one is stationary domain in which the air flows in order to mimic the air flow in a wind tunnel and other is rotating domain which is two times the diameter of turbine. Turbine will rotate along this rotating domain with a fixed rotational velocity, which will be input during the analysis. The relative motion between the stationary and rotating domain is realized by sliding mesh technique.

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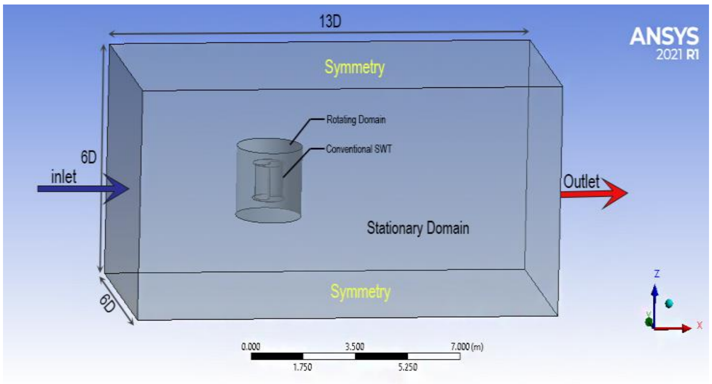


Fig -4: Computational domain for analysis

The entire domain is represented in terms of turbine diameter(D), the air will enter the domain from inlet at 7m/s and the rotating domain will rotate with the given rotational velocity to simulate the turning effect.

3.2 Mesh generation

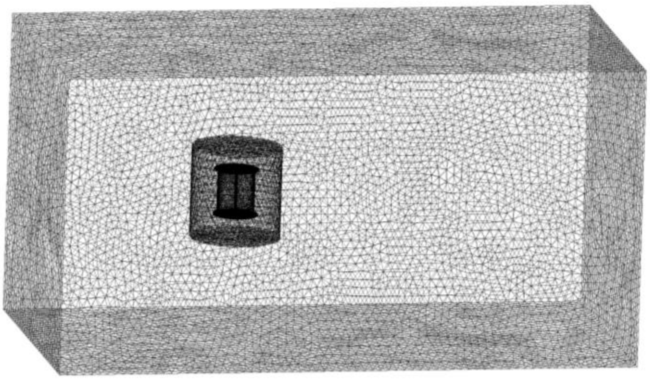


Fig -5: Generated mesh for CSWT

The computation grid was generated using the MESH tool in ANSYS Workbench. The three-dimensional mesh is composed of tetrahedral mesh, grid node density is utilized in the rotating domain which will increase the number of elements than in the stationary domain. Prism layer grid elements were generated at the edges of the turbine in order to increase the mesh quality and to capture the boundary layer flow over blades of the turbine, the height of the first prism layer above the surface was set such that the y+ value for the first elements from the wall will be close to 1 for a given rotation velocity of the rotor and the position of the elements on the blade. Maintaining y+ value at 1 will help us to avoid additional wall functions. Total 12 prism layers at a growth rate of 1.2 was used to generate the mesh.

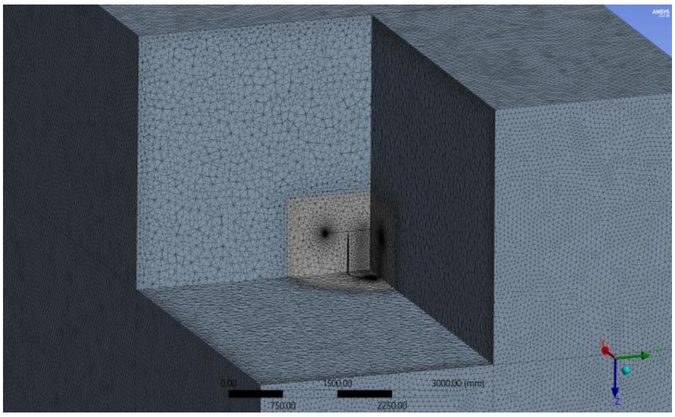


Fig -6: Sectional view of the generated mesh

Initial properties of the air used in the analysis are mentioned in the below tabular form

Table -3: Initial conditions incorporated into pre-processing

Properties	**Values**
Fluid type	Air
Density of fluid (ρ)	1.225 kg/m^3
Fluid Viscosity (μ)	1.789×10^{-5} Ns/m^2
Specific Heat	1.4
Analysis Model	k-ω SST

The same computational procedure is adopted for analysis of modified spline savonius wind turbine.

4. RESULTS AND DISCUSSION

In this section results of both CSWT and modified spline savonius wind turbine with aspect ratio 1 are reported in detail for five different angular speeds. Starting from data average of a rotation, a comparison between CFD and wind tunnel is proposed. Simulations have been conducted with uniform incident wind speed in order to reproduce the same conditions of wind tunnel tests and validate the case. Real wind characteristics and changes in wind speed and direction could influence the performance requiring specific investigation and analysis of such conditions.

4.1 Results of CSWT

The flow analysis performed on the CSWT at different tip speed ratios and the variation in torque coefficient(C_m) at different TSR is calculated as the average of last three revolutions of the turbine. Power coefficient (C_p) is also calculated for all five TSRs and the variation in these parameters are analyzed with the help of a graph. In the graph shown below the variation in the instantaneous torque at different azimuthal angles.

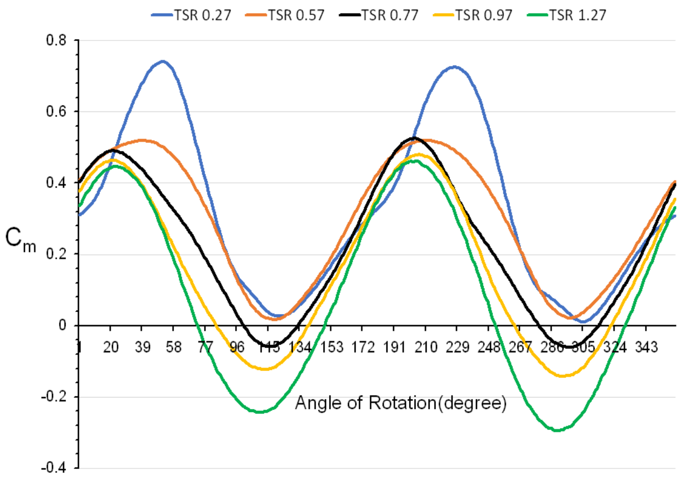
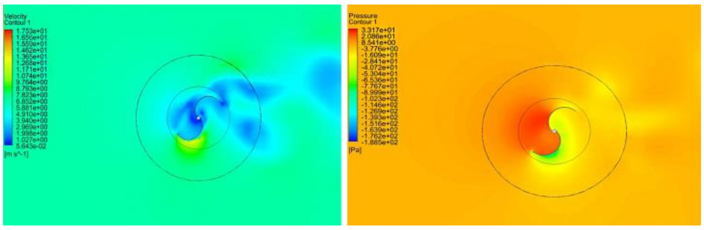


Fig -7: Variation in C_m at different TSR

Table -4: 3D CSWT model data at different TSR

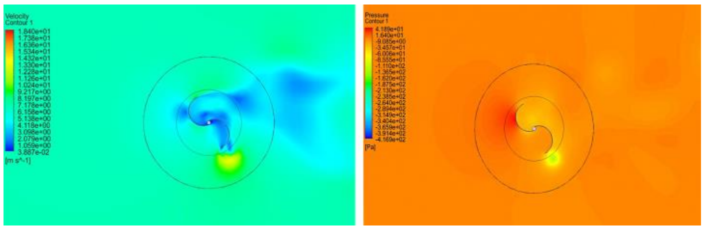
TSR	Cm	Cp
0.27	0.326	0.0882
0.57	0.293	0.1672
0.77	0.217	0.1677
0.97	0.157	0.1526
1.27	0.084	0.1077

From the above data we can observe that peak power coefficient is obtained at 0.77 TSR and highest intantaneous torque coefficient is observed at 36° and lowest at 115°. Fig 8-9 shows variation in velocity and pressure gradients across the blade at 0.77 TSR.



(a) (b)

Fig -8: Velocity contours(a) and Pressure contours(b) at 36° of CSWT



(a) (b)

Fig -9: Velocity contours(a) and Pressure contours(b) at 115° of CSWT

At 36 degree angle of rotation the even pressure distribution across the turbine the pressure at left half of the turbine is more than the right side hence the instantaneous torque generated is high, while the negative torque is produced at 115 degree due to the depression region developed at the end of advancing blade.

4.2 Results of modified spline SWT

The variation in torque coefficient (Cm) at different TSR is calculated for the modified spline SWT in the similar way as the CSWT.

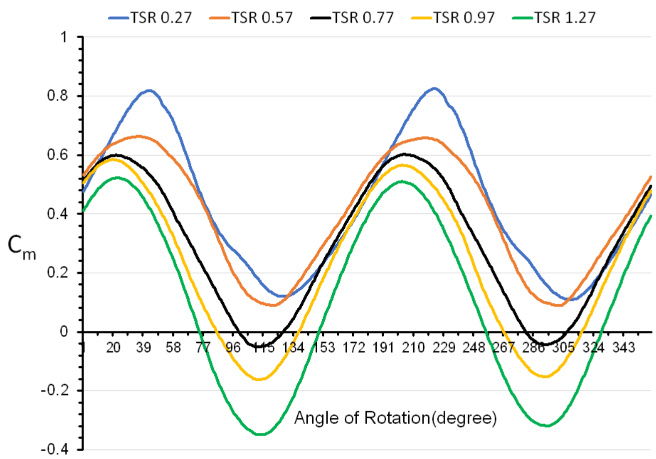


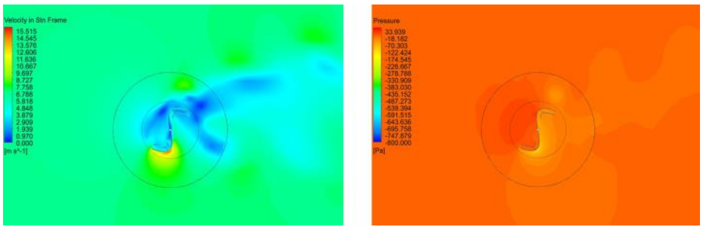
Fig -10: Variation in C_m at different TSR

Table -5: 3D modified spline SWT model data at different TSR

TSR	Cm	Cp
0.27	0.429	0.1159
0.57	0.398	0.2269
0.77	0.298	0.2301
0.97	0.219	0.2124
1.27	0.099	0.1258

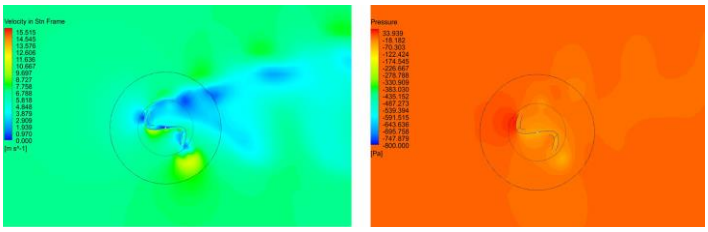
From the above data we can observe that peak power coefficient is also obtained at 0.57 TSR and the torque coefficient for modified spline SWT is higher than the CSWT.

The highest instantaneous torque is observed at 45° and lowest at 135° of the turbine rotation. Fig 11-12 shows the variation in velocity and pressure gradient across the blade at 0.77 TSR



(a) (b)

Fig -11: Velocity contours (a) and Pressure contours (b) at 45° of modified spline SWT



(a) (b)

Fig -12: Velocity contours (a) and pressure contours (b) at 135° of modified spline SWT

The higher torque coefficient is observed in the turbine at 35 degree is due to the small flow separation at the concave side of the scooplet which is attached to advancing blade and the negative C_m is observed at 135 degree of rotation is due to the depression region developed at the end of advancing blade similar to the CSWT model, but in modified spline SWT the scooplet found it's use in reducing the negative torque produced which is slightly lower than in the CSWT case which can be observed from Fig -10. In both cases high C_m is obtained in the range of 25-36 degrees and lowest C_m can be observed from 115-135 degrees angle of rotation.

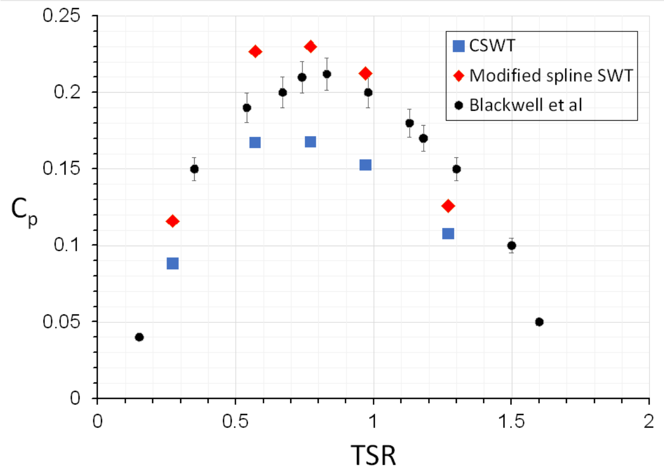


Fig -13: Cp obtained from 3D computational models and experimental data from blackwell

The power coefficients of the two 3D CFD models at different TSR are compared with the experimental data from blackwell data book. We can observe from from the above graph that the 3D CFD analysis of the classical savonius wind turbine displayed underestimation of the actual physical model. Modified spline SWT showed higher Cp when compared to the experimental and numerical models of CSWT, highest Cp is obtained at TSR of 0.77 for two 3D models and for actual physical model at TSR 0.8.

5. CONCLUSIONS

The Savonius wind turbine a class of vertical axis wind turbine can be viable option for small scale, low cost of grid energy conversion in certain cases of confined space and low wind speed region, where the other turbines cannot work efficiently. However the existing design of conventional Savonius wind turbine is yet a matter of research to make it more useful in situations. In this context the present study attempts to improve the performance of CSWT by evolving a new concept of modified spline type savonius wind turbine. In this work the importance given for proper distribution of pressure and velocity by introducing scooplets which are offset from spline curve of the turbine. The CFD analysis carried out in ANSYS FLUENT using transient, k-ω SST turbulence model and it is compared with experimented conventional model which taken as reference. In this study it is clear that modified spline SWT showed better performance than the classical one.

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