**Analyzing the Impact of Tip Speed Ratio on Vertical Axis Wind turbine modeling in 2D and 3D Environments using the Computational Fluid Dynamics**

Dr. Bharat Singh Chauhan1,2[0000-0002-6155-1880] and Krishan Dutt Yadav1,2[0009-0001-8719-4084]

1 Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh- 201 002, India.

2 HSS Group, CSIR- Central Building Research Institute, Roorkee, Uttarakhand-247667, India.  
bharat32@gmail.com

**Abstract.** The recent depletion of fossil fuel reserves and changes in the global environment led by an increase in atmospheric pollution are making people explore for renewable energy sources. Due to its many advantages over the traditional horizontal axis wind turbine (HAWT), such as its ease of maintenance, superior efficiency in wind farms, and lack of requirement for yaw control, the industry has been moving progressively in preference for vertical axis wind turbines (VAWT) in recent years. In this paper, computational fluid dynamics simulation with ANSYS Fluent software is used to study the effectiveness and performance of VAWT. This study uses the unsteady Reynolds-averaged Navier-Stokes (URANS) model to simulate three-bladed VAWT in 2D and 3D Environment. Using a three-bladed VAWT having fixed blade profile, rotor diameter, chord length, and setting angle, the current work systematically investigates the impact of various tip speed ratios (TSR) on VAWT performance (i.e., understands the effect of TSR on the efficiency). Subsequently, the TSR of 2, 2.5, and 3 are taken in order to understand its influence, after the results have been verified with the review of existing literature. To achieve optimal VAWT performance, it is imperative to choose a TSR within a specific range, as it significantly affects the numerical results.

**Keywords:** Computational Fluid Dynamics (CFD), ANSYS Fluent, k-ω SST Turbulence Model, URANS, VAWT.

1. Introduction

Fossil fuels being the most popular option for the satisfying energy demand of current generations comes with the challenge of climate change. Wind energy, being the most promising renewable energy source, is crucial in addressing the fossil fuel crisis[1]. A wind turbine is a technological advancement that enables the conversion of wind's kinetic energy into practical mechanical energy[2]. Based on the orientation of their axis of rotation, modern wind turbines are divided into two categories: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs)[3]. Growing interest has been shown recently in vertical-axis wind turbines (VAWTs) for wind energy which is attributed to their omnidirectional capability, minimal installation and maintenance costs, scalability, and dependability[4]. The Darrieus type vertical axis wind turbines (VAWTs) is a lift-based turbine that uses blades with cross sections shaped like airfoils have a simpler structure than HAWTs since they don't require a yaw control mechanism to operate in any direction of flow. Typically, VAWTs feature straight blades because they are simpler to produce than HAWTs' twisted blades. Furthermore, the ground placement of the generator and gearbox is made feasible by the design of VAWTs, which can simplify installation and maintenance. When compared to HAWTs, all of the features in VAWTs can lower their cost[5].

1. Literature Review

Duty, D. et al. (2013): This paper presents a two-dimensional (2D) computational fluid dynamics (CFD) analysis of a vertical axis wind turbine (VAWT). The purpose of the study is to use CFD simulation to look into the VAWT's performance and flow characteristics. The simulation provides an understanding of the velocity and pressure distribution surrounding the turbine, as well as the power coefficient and overall efficiency of the turbine, by modeling the turbine shape, the boundary condition involved, and the meshing and solver settings. As a crucial step in guaranteeing the validity and dependability of the simulation results, this study also assesses the experimental result's validation and compares it with the published journal [6].

Sibagariang, P., Y. et al. (2013): The main goal of this work was to carry out numerical investigation for the performance of an H-Darrieus Vertical Axis Wind Turbine (VAWT) which is affected by the tip speed ratio. The NACA 4155 airfoil turbine blade is the subject of the simulations. Tested are the following four tip speed ratios: 0.5, 1.0, 1.5, and 2.0. The power coefficient is computed using the average wind speed as it exits the turbine. Here, it can be concluded that tip speed ratio has a significant impact on power. The power will grow as the tip speed ratio increases [2].

Tjiu, W. et al. (2014): The central focus is to evaluate the configurations of Darrieus vertical axis wind turbines (VAWTs), highlighting the shortcomings of each variation that impeded the evolution into large-scale rotor technology. An extensive chronology is provided as a pedigree diagram. The performance, components, and operational reliability of the variations are evaluated. Furthermore, the existing state and potential directions of Darrieus VAWT are discussed [9].

Rezaeiha, A. et al. (2017): The main purpose of the current study is to predict the performance of a vertical-axis wind turbine (VAWT) using 2-dimensional simulations with the unsteady Reynolds-averaged Navier-Stokes (URANS) and a domain size large enough to minimize the effects of blockage and uncertainties in the boundary conditions using computational fluid dynamics (CFD) simulation [4].

Celik, Y. et al. (2020): The main motivation for this work is to create a CFD start-up model in order to assess the self-starting behaviour of the H-type vertical axis wind turbines (VAWTs). In order to ensure the conservation of mass and momentum throughout the simulation, the computing domain is divided between a rotational domain, which houses the rotor, and a fixed rectangular outer domain. In order to guarantee the establishment of continuity in the flow field, interface boundary conditions are used to link the two regions. The blade surfaces are regarded as no-slip limits, and a zero-gauge pressure outlet is placed on the right side of the computational domain [7].

Parker, M., C. et al. (2021): The main objective is to carry out turbine model tests in the wind tunnel of a single VAWT at practical working Reynolds numbers and tip speed ratios. The wake's structure is mostly influenced by the tip speed ratio and varies only somewhat with the Reynolds number. Both time-averaged and phase-averaged data were used to get these results, which demonstrate a substantial dependence on the tip speed ratio in vertical-axis wind turbines [8].

1. Methodology
   1. Parameters of VAWT

The 2D and 3D model is used for numerical simulation in this research. Different parameters used for analysis are presented in Table 1.

Table 1 Parameters of VAWT

|  |  |
| --- | --- |
| Blade type | NACA0015 |
| Blade height | 3m (for 3D) |
| Diameter of Rotor (D) | 2.5m |
| Chord length | 0.40 (40% of NACA0015 Original) |
| Wind speed | 10m/s (Constant) |

NACA0015 Airfoil coordinates are taken from http://airfoiltools.com [11] shown in Fig.1 which is initially taken as open at trailing edge, later trailing edge closed in modeling tool.

|  |
| --- |
|  |
| **Fig. 1.** NACA0015 Airfoil [11] coordinates |

Reynolds numbers (*Re*) for this research is 2×106 (approximately) which is calculated by

Where , *V, D* and are the density of air, Velocity, Diameter and dynamic viscosity respectively.

* 1. Boundary Conditions

For 2D Analysis:

Left boundary: Velocity inlet (10m/s Constant)

Top and bottom boundary: Specified shear (Zero slip)

Right boundary: Pressure Outlet

Turbine blades: No slip

Shaft: No slip

For 3D Analysis:

Left boundary: Velocity inlet (10m/s Constant)

Top, bottom and sides boundary: Specified shear (Zero slip)

Right boundary: Pressure Outlet

Turbine blades: No slip

The entire computational zone is divided into three parts namely external (stationary), internal (stationary) and middle (rotating) which contains airfoils. The sliding mesh can be built by setting angular velocity of the rotating domain. The interface between each zone is set as the interface condition.

The airfoil surface has a boundary layer mesh installed in order to guarantee the accuracy of the complex flow computation near the wall. The following formula is used to calculate the first layer's thickness:

Where *y+* is dimensionless value of wall distance and *ut* is the wall friction velocity.

Different domain sizes have tried for 2D simulation and findings are recoded. Some of the Domain are attached in this research paper.

2D geometries are prepared on ANSYS Design Modeler for different cases shown in Figs. 2 and 3D geometry is prepared on ANSYS Spaceclaim tool shown in Fig. 5 and 6. For 3D Geometry the distance of inlet, outlet, sides and top and bottom boundaries are 5D, 10D, 2D and 2D respectively. For 2D case meshing method used All Triangle Method shown in Figs. 3 and 4 but for 3D case meshing method is patch confirming method shown in Figs. 7 to 9.

|  |  |
| --- | --- |
| **Fig. 2** 2D Geometry of Domain size | **Fig. 3** Meshing of Domain size |
| **Fig. 4** Refinement around airfoil with inflation (from first boundary layer thickness) | **Fig. 5** 3D Airfoil profile |
| **Fig. 6** 3D geometry of VAWT in ANSYS Spaceclaim | **Fig. 7** Meshing of 3D Computational domain |
| **Fig. 8** Wireframe view of Airfoils | **Fig. 9** Refinement mesh with inflation of Airfoils |

* 1. Turbulence Model Simulations

The turbulence model used in simulation is SST k-ω model. For the simulation TSR=2.5 and moment coefficient is assumed to be 0.1 for airfoil curves. To verify the accuracy of 2D and 3D simulation data of the 3.5Kw VAWT were compared with the McMaster University wind tunnel experimental data [1]. The numerical simulation has a positive direction along the X-axis and a wind speed of 10 m/s for the velocity inlet condition. The pressure outlet condition's gauge pressure is 0 Pa. The windmill turns in a anticlockwise direction. The comparable rotational angular velocity of the wind turbine is 20 rad/s when its TSR is 2.5. Convergence of residuals are set to 1× 10−6.

The pressure-velocity coupling method of SIMPLE and the 2D and 3D unstable incompressible equation are employed for the 2D and 3D numerical simulation model used in this work. Among the available turbulence models, the SST k-ω model is chosen because it is more accurate in capturing the features of the flow field [1].

The main governing transport equations Eq. 1 to 9 of k-ω SST model are as follows [10]:

|  |  |  |
| --- | --- | --- |
|  |  | (1) |
|  |  | (2) |
|  |  | (3) |
|  |  | (4) |
|  |  | (5) |
|  |  | (6) |
|  |  | (7) |
|  |  | (8) |
|  |  | (9) |

Where F1 and F2 are blended functions.

Model constants .

1. Results and Discussions
   1. Power Calculation

Angular velocity of wind turbine for different tips speed ratio is calculated by Eq. 10

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

Where *R*=1.25m is the radius and *Vi* =10m/s is the inlet velocity.

For different tips speed ratios angular velocities are presented in Table 2.

Table 2 Angular velocities for different TSR

|  |  |
| --- | --- |
| TSR | Angular Velocity (rad/s) |
| 2.0 | 16 |
| 2.5 | 20 |
| 3.0 | 24 |

### Theoretical Power Calculation

PTheoretical = (Assumed thickness =1m)

= 0.5×1.225×2.5×103

=**1531.25 Watts**

### Actual Power Calculation

#### Case 1 (For Tip Speed Ratio of 2.5)

This is first case of simulation work, in which tip speed ratio of 2.5 is taken.

Time steps for unsteady/ transient simulation is calculated from below formulas:

Circumference = ΠD = 3.14×2.5=7.85m

Time to complete one revolution t= which comes 0.314 seconds if it is divided by 360 , *dt* will come 0.0008722 seconds which is used for simulation work. Torque Vs time steps graph is shown in Fig. 10 for this case.

|  |
| --- |
| **Fig. 10** Torque Vs Time steps 1st case of simulation (TSR=2.5) |

Actual Power (*Pactual*) = Average torque for 360ᵊ or One cycle (last 360-time steps) × angular speed

Which comes **520.882 watts** and Coefficient of Power (*Cp*) =*Pactual/Pair*=**0.34** and *Cp* experimental is **0.32** [1]. Percentage error is **6.25%** (+Ve).

Case 2 (For Tip Speed Ratio of 2.0)

In this case Actual power comes **457.638 watts** and *Cp* comes **0.2988**. Which is very near to experimental ***Cp* =0.32** [1]. percentage error is **6.625%** (-Ve). Torque Vs time steps graph is shown in Fig. 11for this case. For the lower tips speed ratio smooth Torque vs time steps graph was not observed.

|  |
| --- |
| **Fig. 11** Torque Vs Time steps for 2nd case of simulation work (TSR=2.0) |

Case 3 (For Tip Speed Ratio of 3.0)

In this case Actual power comes **380.745 watts** and *Cp* comes **0.25**. Which is far from experimental ***Cp* =0.32** [1]. Percentage error is **21.87%.** Torque Vs time steps graph is shown in Fig. 12 for this case.

|  |
| --- |
| **Fig. 12** Torque Vs Time steps for last case of simulation work (TSR=3.0) |

Case 4 (3D Case0)

3D geometry shown in Fig. 6 is simulated on ANSYS Fluent with same turbulence model. 3D geometry simulation is still under process. Results obtained till now from 3D simulation are presented here. As 3D geometry has very large no. of nodes in meshing, its need more computational power. Torque Vs time steps graph is shown in Fig. 13for this case.

|  |
| --- |
| **Fig. 13** For 3D geometry Torque vs Time steps (TSR=2.5) |

It is taking large time to produce/Converge the results. In this case Actual power comes **373.634 watts**

1. Visualization of results

All the post-processing of results is done on ANSYS CFD post. In this section Pressure contours and velocity streamlines are presented. Pressure contours around airfoils in 2D simulation for different cases are presented below from Figs. 14 to 19. Velocity streamlines for 2D simulations are shown in Fig. 20 to 22. For 3D Geometry pressure contour on turbine blades and velocity streamlines are presented in Fig. 23 and Fig. 24 respectively.

|  |  |
| --- | --- |
| **Fig. 14** Pressure contour of turbine blades for case 1 | **Fig. 15** Zoom view of Pressure contour of turbine blades for case 1 |
| C:\Users\Bharat Singh\Desktop\KD YADAV\VAWT_IDRI\tsr 2 pressure contour around blades.png  **Fig. 16** Pressure contour of turbine blades for case 2 | C:\Users\Bharat Singh\Desktop\KD YADAV\VAWT_IDRI\tsr 2 pressure contour around blades zoom.png  **Fig. 17** Zoom view of Pressure contour of turbine blades for case 2 |
| E:\SEMINAR\VAWT_IDRI\pressure countour tsr 3.png  **Fig. 18** Pressure contour of turbine blades for case 2 | E:\SEMINAR\VAWT_IDRI\pressure countour tsr 3 zoom.png  **Fig. 19** Zoom view of Pressure contour of turbine blades for case 2 |
| **Fig. 20** Velocity streamlines of turbine blades for case 1 | E:\SEMINAR\VAWT_IDRI\tsr 2 velocity streamlinesr around blades zoom.png  **Fig. 21** Velocity streamlines of turbine blades for case 2 |
| E:\SEMINAR\VAWT_IDRI\velocity streamline tsr3.png  **Fig. 22** Velocity streamlines of turbine blades for case 3 | |
| **Fig. 23** Pressure Contours on single turbine blade 3D | **Fig. 24** Velocity streamlines of 3D turbine blades |

1. Conclusions

Using 2D and 3D URANS CFD simulations, the current work examined the impact of tip speed ratio variation on VAWT performance.

Major derived conclusions are as follows:

1. The performance will be greatly overestimated if the result is sampled before the flow becomes stable.
2. The Tip Speed Ratio of 2.5 is found to give the power coefficient result closest to the experimental results for the VAWT under consideration.
3. It has been shown that the minimum distance of 5D between the turbine center and the inlet will minimize the impact of the domain inlet on the turbine's performance. The value of *Cp* obtained for this condition is 0.34 for TSR 2.5. This leads to a lower percentage error in *Cp* of 6.25% for the TSR 2.5 (with respect to available experimental work), which is within the permissible limit.
4. From the results of the simulation work, it is clear that with increasing the tip speed ratio from 2 to 2.5 the *Cp* value is increased from 0.31 to 0.34, while the experimental *Cp* is 0.32. This is because of zone of backflow (negative velocity) is not observed at the low tip speed ratio.
5. The maximum positive pressure on the wind turbine blades is noted to increase with the increase in the tip speed ratio.
6. The minimum pressure on the wind turbine blades is noted to be least for the tip speed ratio of 2.5, thus resulting in a higher power output.
7. Further increasing tip speed ratio from 2.5 to 3 the *Cp* value is reduced from 0.34 to 0.25, where the experimental *Cp* is 0.32. This is because of the presence of zone of backflow (negative velocity) at high tip speed ratio.
8. The value of drag coefficient for TSR of 2, 2.5 and 3 are 1.16, 1.10 and 1.25 respectively, which indicates that corresponding to high tip speed ratio value of drag coefficient is higher resulting into low value of *Cp*.
9. References

[1] L. Zhang, Y. Liang, X. Liu, Q. Jiao, and J. Guo, “Aerodynamic Performance Prediction of Straight-Bladed Vertical Axis Wind Turbine Based on CFD,” Adv. Mech. Eng., vol. 2013, Apr. 2013, doi: 10.1155/2013/905379.

[2] Y. P. Sibagariang, I. Pramono, K. Kishinami, and H. Ambarita, “Effects of tip speed ratio on the performance of an H-Darriues wind turbine with NACA 4415 air foil,” AIP Conf. Proc., vol. 2221, no. 1, p. 060005, Mar. 2020, doi: 10.1063/5.0003480.

[3] M. Yi and Q. Jianjun, “Numerical Study of Flow Field and Aerodynamic Performance of Straight Bladed VAWT at Variable Tip Speed Ratios,” Open Mech. Eng. J., vol. 9, pp. 1017–1024, Oct. 2015, doi: 10.2174/1874155X01509011017.

[4] A. Rezaeiha, I. Kalkman, and B. Blocken, “CFD simulation of a vertical axis wind turbine operating at a moderate tip speed ratio: Guidelines for minimum domain size and azimuthal increment,” Renew. Energy, vol. 107, pp. 373–385, Jul. 2017, doi: 10.1016/j.renene.2017.02.006.

[5] T. Zhang et al., “Winglet design for vertical axis wind turbines based on a design of experiment and CFD approach,” Energy Convers. Manag., vol. 195, pp. 712–726, Sep. 2019, doi: 10.1016/j.enconman.2019.05.055.

[6] D. Duty et al., “Performance Analysis of VAWT with H-Darrieus Rotor using 2D CFD Modelling,” vol. 5, pp. 5–10, Apr. 2023.

[7] Y. Celik, L. Ma, D. Ingham, and M. Pourkashanian, “Aerodynamic investigation of the start-up process of H-type vertical axis wind turbines using CFD,” J. Wind Eng. Ind. Aerodyn., vol. 204, p. 104252, Sep. 2020, doi: 10.1016/j.jweia.2020.104252.

[8] Colin M. Parker and Megan C. Leftwich, “The effect of tip speed ratio on a vertical axis wind turbine at high Reynolds numbers,” Exp Fluids (2016) 57:74, DOI 10.1007/s00348-016-2155-3.

[9] W. Tjiu, T. Marnoto, S. Mat, M. H. Ruslan, and K. Sopian, “Darrieus vertical axis wind turbine for power generation I: Assessment of Darrieus VAWT configurations,” Renew. Energy, vol. 75, pp. 50–67, Mar. 2015, doi: 10.1016/j.renene.2014.09.038.

[10] ANSYS, ANSYS Fluent User Guide 13.0 ANSYS, Inc.

[11] https:/airfoiltools.com