Chapter 3

Numerical Modeling and Wind Tunnel Testing of Vertical Axis Wind Turbine

After the review of exhaustive literature on vertical axis wind turbine, it is understood that there is need of vertical axis wind turbine which will work efficiently and will be more stable as compared to its counterparts. The work of developing an innovative vertical axis wind turbine starts with modelling of different possible creative configurations of vertical axis wind turbine. The prerequisite knowledge essential work of developing the different configurations is Wind aerodynamics. Primitive shapes like concave and convex shapes are used predominantly in design of wind turbine. In Section 3.1, Fundamentals of Computational Fluid Dynamics is explained. Further, in Section 3.2, Comparative study of results for one, two and three storey vertical axis wind turbine is made, in terms of self-starting speed,
coefficient of power, drag and lift coefficient, pressure and velocity distribution.

### 3.1 3-D Computational Fluid Dynamics (CFD) Modelling

Multi-storey Vertical Axis Wind Turbine (VAWT) 3-D CFD models are developed using commercial CFD package ANSYS FLUENT [67]. The brief description of modelling approach of these turbines is given in this section. Conservation of momentum in an inertial (non-accelerating) reference frame is described by

\[
\frac{\partial p}{\partial t} \left( \rho \nu \right) + \Delta \cdot (\rho \nu \nu) = -\Delta \rho + \Delta (\bar{\nu}) + \rho \bar{g} + \bar{F}
\]

(3.1)

The equation for conservation of mass, or continuity equation, can be written as follows:

\[
\frac{\partial \rho}{\partial t} + \Delta \cdot (\rho \bar{\nu}) = S_m
\]

(3.2)

To perform the dynamic simulation, Moving Reference Frame (MRF) has been used. As shown in Fig 3.1 the MRF is activated in selected zone that modifies the equation of motion with additional terms for acceleration which occurs due to transformation from stationary to MRF. The turbine is enclosed in MRF co-axially [67].
Figure 3.1: Moving Reference Frame principle

Figure 3.2: Turbine model placed in Moving Reference Frame and stationary computational domain and meshing
The axis of rotation is defined by a unit direction vector \( \hat{a} \) such that

\[
\vec{\omega} = \omega \hat{a}
\]  

(3.3)

Fig 3.2 shows the computational domain for the CFD problem with respect to the rotating frame such that an arbitrary point in the CFD domain is located by a position vector \( \vec{r} \) from the origin of the rotating frame. Fluid velocities can be transformed from the stationary frame to the rotating frame.

The solver uses pressure based absolute velocity with steady time. Shear-Stress Transport (SST) \( k - \epsilon \) standard turbulence model with standard wall function is used for the analysis. The SST model is a two-layer model which employs the \( k - \epsilon \) model of Wilcox \[70\] in the inner region of boundary layers and switches to a \( k - \epsilon \) model in the outer region of boundary layers and in mixing regions. The outer \( k - \epsilon \) model is transformed to provide a second set of \( k - \omega \) equations with a blending function used to transition between the two sets of equations. This model performs well with free shear flows, flat plate boundary layer flows, complicated adverse pressure gradient flows and separated flows \[68\].

3.2 Results and Discussion

The three turbine models viz: one storey, two storey and three storey vertical axis wind turbine are modeled in ANSYS Design modular and simulated in FLUENT. Simulations are carried out for estimation of torque. Prototypes of turbine models are fabricated. Wind tunnel testing of the prototype models is conducted for estimation of performance parameters like self starting wind speed and coefficient of power.
Fig. 3.3 shows storey details of turbine with locations and sizes of three flaps and two blades.

NACA 68-613 cambered aerofoils is selected for analysis as cambered aerofoil has better self-starting capability as compared to symmetrical aerofoils. Two blades of the storey are arranged with opposite leading and trailing edge so that the effect
of drag forces at 90° and 180° assist the motion of the wind turbine. Lift force acting on the rotor blades tangentially to the plane of the rotation is producing torque. Flaps used are made up from rectangular plate ‘S’ shape so as to have combination of concave and convex shape. Concave shape of the flap gives the major driving force as it has more drag coefficient than convex shape,

![First Story Second Story Third Story](image)

Figure 3.4: Position of blades and flaps per storey

which further augments the speed of the turbine rotor. Three flaps per storey are used, in which the central flap has bigger radius of curvature as compared to flaps on either side of it. At any position of the turbine at least two flaps viz: central flap and either of the side flaps are exposed to wind so that maximum wind force can be applied on the turbine. For two-storey turbine, two one-storey turbines are attached orthogonal to each other whereas for three-storey turbine, three one-storey turbines are attached with first and third storey orthogonal to second storey. Fig. 3.4 shows the arrangement of blades and flaps for different storeys. The heights of one, two and three-storey turbines are 70 mm, 140 mm
and 210 mm, respectively.

3.2.2 Wind Tunnel Setup

Wind tunnel testing is carried out for three models of Multi-storey Vertical Axis Wind turbines to measure the minimum self-starting wind speed and breaking torque. Fig. 3.5 shows the schematic diagram of wind tunnel test setup with turbine located in the test section. The figure shows the wind tunnel test section of 1000 mm length and 300mm X 300 mm in cross section. The figure also shows other components of wind tunnel as contraction section and diffuser section.

Fig. 3.6 shows the prototypes of one, two and three-storeys wind turbines mounted within the wind tunnel test section. The array of vane axial fan arranged in two rows which drive the flow velocity up to 30 m/s. The flow from the fans is initially conditioned through pair of settling screens. Wind speed is measured by using anemometer mounted at mid height of the turbine. Digital tachometer is used to measure the turbine rotational speed and torque sensor of four point contacts is used to measure breaking torque. The minimum wind speed required for self-starting the turbines are measured at orientation with respect to wind direction. Breaking torque is measured at different tip speed ratio.

Three VAWT models are developed with one, two and three storeys as shown in Fig. 3.6.
Figure 3.5: Wind tunnel set up
Figure 3.6: Prototypes of three turbine models
3.2.3 Minimum Wind Speed Requirement for Self-Start

The concept of multi-storey turbine is demonstrated experimentally with wind tunnel testing of three turbines. The minimum wind speed required for self-start for one-storey turbine is highly dependent on the orientation of turbine with respect to wind speed. During experimentation it was observed that when blades are orthogonal to wind flow direction, turbine could not self-start for even up to wind speed of 15 m/s. For the blade orientation parallel to wind flow direction, the minimum wind speed required was about 7 m/s. On the contrary, in multi-storey turbines could self-start for any orientation. Two-storey turbines show the minimum wind speed requirements to self-start are in the range of wind velocity 2.4 m/s - 3.3 m/s whereas three-storey turbine show this requirement in range of 2-2.6 m/s for different orientation of turbines. Multi-Storey turbines show that at any given orientation at least one storey is aligned with wind flow direction and hence improvement in self-start wind speeds.

3.2.4 Blockage Factor

When the turbine is placed in a wind tunnel, the object produces some tunnel blockage which causes an increase in the local wind velocity in the section. This increase has to be accounted for the blockage factor ($\epsilon$) which is calculated by relating the maximum swept area of the turbine $A_S$ to the cross-sectional area of the wind tunnel test section $A_T$ \[69\]. The corrected velocity is given by:

\[ v_c = v (1 + \epsilon) \]  \hspace{1cm} (3.4)

where, wind tunnel blockage rate
\[ \epsilon = \frac{A^p}{A_T} \]  \hspace{1cm} (3.5)

The corrected velocity is illustrated in table 3.1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Air velocity</th>
<th>Wind Tunnel Blockage rate</th>
<th>Corrected velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-Storey</td>
<td>9</td>
<td>0.0388</td>
<td>9.3492</td>
</tr>
<tr>
<td>Two-Storey</td>
<td>5.5</td>
<td>0.0777</td>
<td>5.927</td>
</tr>
<tr>
<td>Three-Storey</td>
<td>5.5</td>
<td>0.1166</td>
<td>6.141</td>
</tr>
</tbody>
</table>

Table 3.1: Specimen corrected velocities for wind tunnel tests for three turbines

### 3.2.5 Power Coefficient Performance

The power coefficient \( C_p \) is the ratio of actual power to the available power in wind.

\[ C_p = \frac{P_{\text{actual}}}{0.5 \rho A v^3} \]  \hspace{1cm} (3.6)

Where actual power is given by

\[ P_{\text{actual}} = \frac{2 \pi N T}{60} \]  \hspace{1cm} (3.7)

Power coefficients \((C_p)\) obtained experimentally and numerically varies due to method of calculating torque given in equation 3.7. The torque value is measured during wind tunnel tests and also calculated using CFD simulation. Torque estimation using CFD explained in following paragraphs.

As shown in Fig. 3.7, in fluid flow calculations, total elementary force \( \vec{F}_T \) can be decomposed about vector \( \vec{a} \) into normal and tangential direction with regards
to small elementary area, where force acts. Normal force created by pressure is called pressure force $\vec{F}_P$. Tangential force created by viscosity is called viscous force $\vec{F}_v$.

![Figure 3.7: Force distribution](image)

$$F_T = \vec{a}\vec{F}_P + \vec{a}\vec{F}_v$$  \hspace{1cm} (3.8)

As shown in Fig. 3.8 the total moment vector $[\vec{M}_A]$ about a specified centre $A$ is computed by summing the cross products of the pressure and viscous force vectors for each face with the moment vector $\vec{r}_{AB}$, which is the vector from the specified moment centre $A$ to the force origin $B$. The terms in this summation represent the pressure $[\vec{r}_{AB} \times \vec{F}_P]$ and viscous moment vector $[\vec{r}_{AB} \times \vec{F}_v]$. 

Figure 3.8: Moment force diagram

\[ \vec{M}_A = \vec{r}_{AB} \times \vec{F}_P + \vec{r}_{AB} \times \vec{F}_v \]  \hspace{1cm} (3.9)

The value of \( [\vec{M}_A] \) in the CFD analysis is equivalent to the torque required for the calculation of actual power \( P_{\text{actual}} \).

To obtain the values of torque using CFD, MRF is enclosed in computational flow domain. As shown in Fig. 3.2, fluid domain is considered of cylindrical shape. To avoid the blockage effects, fluid domain is extended in axial direction about four times diameters upstream and eight times diameters downstream of the rotor whereas fluid flow domain diameter is considered three times the rotor diameter. The left side of the domain is treated as velocity inlet. The inlet velocity is varied.
as per the wind velocity. The right side of the fluid domain is treated as outlet where pressure is assigned as $0 \ Pa$. The turbine and MRF wall is considered as moving wall with rotational velocity along $Z$ axis with no slip. Cell zones created are turbine, MRF and computational flow domain.

![Graph](image1)

(a) One-storey model

![Graph](image2)

(b) Two-storey model

![Graph](image3)

(c) Three-storey model

Figure 3.9: Analysis of mesh independence of numerical results

The analysis is performed for various inlet velocities with zero pressure at
outlet. Number of nodes required for numerical simulations are decided based on the stable value of torque. Fig. 3.9 shows the variation of torque with respect to number of nodes for the three turbine models. Number nodes required to get the stable torques values are about 35,000 nodes, 1,15,000 and 1,50,000 nodes for one-storey, two-storey and three-storey turbines, respectively.

Further, this torque is also obtained experimentally using torque transducer. Wind tunnel tests are carried out to measure this torque at various values of Tip Speed Ratio (TSR) by varying the wind speed. TSR is the ratio of blade tip speed to the wind speed. With the help of measured torque, power coefficient $C_p$ values are obtained for various $TSR$. 
Figure 3.10: Power coefficients for three turbine models
Based on the torque values, power coefficient are obtained for various TSR using numerical method and experimental approach. Fig.[3.10] shows the values of power coefficients obtained at various operating range of TSR. The experimental operating range of TSR for one-storey turbine is 0.12-0.45, for two-storey turbine is 0.19-0.80 and for three-storey turbine is 0.40-1.38. For these operating range of TSR, the power coefficient values obtained through wind tunnel test are 0.62-4.40%, 3.15-22.06% and 6.50-26.13%. For the operating range of TSR, numerically obtained power coefficients for three turbines are 0.76-4.86%, 3.88-23.58%, and 7.80-28.00%, respectively. Numerically and experimentally calculated values are in close agreement. Power performance of three-storey turbine is considerably good compared to other turbines.

The numerical values of $C_p$ in Fig. [3.10] are obtained by considering the torque values at azimuth angle $0^\circ$. However, the torque values show variation with respect azimuth angle. Fig. [3.11] shows the variation of the torque values for three turbine models with respect to azimuth angle obtained for TSR value of 0.44. Three-storey turbine shows large variation in torque values with respect to azimuth angle as compared to other turbines. For all the turbines the highest values of torque are observed at $150^\circ$ whereas lowest values of torque for three-storey and two-storey turbines are observed at $90^\circ$. The lowest value of torque in case of one-storey turbine is obtained at $30^\circ$. 
3.2.6 Drag and Lift Coefficient

The drag force and lift force depends upon reference area, wind speed, air density and turbine configuration. The configuration effects of the turbine are taken into account through drag coefficient, lift coefficient and the reference area. The drag force in this turbine is resulting from integrated effect of static pressure acting normal to the surface resolved in drag direction.

Turbine parts facing the wind are having concave and convex shape which augments the starting of turbine at low wind speeds with increased torque.

In the selected turbine designs, the major contribution of drag force comes from three flaps in between two blades. Fig. 3.12 shows the drag and lift coefficients at azimuth angle of 0° for various TSR values. Drag force generated around three-storey turbine is highest as compared to other turbines. The higher value of drag force in three-storey turbine results in higher value of torque. From the plot of drag coefficient values it is evident that the maximum drag coefficient
values are obtained for three storey turbine which is 0.55 at 0.84 TSR compared to 0.08 at 0.16 TSR and 0.34 at 0.72 TSR for one storey and two storey wind turbines. From the plot of lift coefficient values, it is observed that the maximum lift coefficient is available for three-storey turbine which is 0.32 at $TSR$ of 0.85 whereas these values are 0.18 and 0.05 at $TSR$ of 0.50 and 0.84 for one-storey and two-storey turbines, respectively. The drag and lift coefficients analysis of three-storey turbine indicates that the drag force as well as lift force contribute in improving the torque performance.

![Figure 3.12: Drag and Lift coefficients at various orientation for $TSR$ of 0.44](image)

Fig. 3.13 shows the plots of drag and lift coefficients at different azimuth angles
for $TSR$ value of 0.44. The drag coefficient variation with respect to azimuth angle show similar trends for all the three turbines. The first peak of drag coefficients is observed at azimuth angle of 60° whereas lowest values of drag coefficients are observed at azimuth angle of 120°. The second peak of drag coefficients is observed at azimuth angle of 150°. In case of lift coefficients also, similar trends of variation of lift coefficients with respect to azimuth angle are observed. In case of lift coefficients, first peak and second peak have almost same values at azimuth angles of 30° and 150°, respectively. Lowest values of lift coefficients are observed at azimuth angle of 90°.

Figure 3.13: Drag and Lift coefficients at various TSR for orientation of 0°
3.2.7 Static Pressure and Velocity Distribution

Static pressure behaviours obtained using numerical analysis for the three configurations are in the Fig3.14. The figure shows that the pressure magnitude is maximum at upstream side and goes on a decreasing towards the downstream side of the turbine. Similarly, the velocity distribution obtained numerically for these turbines is shown in Fig3.15.

![Static Pressure Contours](image)

Figure 3.14: Static pressure contours for three turbine models
From these plots, it is evident that velocity magnitude increases from centre of the turbine towards the periphery which indicates the correctness of the numerically simulated results.
Figure 3.16: Maximum pressure distribution at various TSR for orientation of 0°

Figure 3.16 shows Maximum pressure difference values at various TSR. Figure shows the highest pressure difference of around 2000 Pa at TSR of 0.9 for three storey turbine. The value of maximum pressure difference for other two turbines are quite low.

3.3 Summary

In this chapter, performance obtained using CFD analysis are compared with the wind tunnel test results. The wind tunnel test shows that three storey turbine
gives considerably good self starting wind speed performance. Further, the power coefficient performance is compared with the wind tunnel test result. This chapter gives detailed insight about other performance.