Numerical Investigations on the Performance Degradation of a Vertical Axis Wind Turbine Operating in Dusty Environment

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1. Abstract

Rapid increase in global energy requirements has resulted in considerable attention towards energy generation from the renewable energy sources. In order to meet renewable energy targets, harnessing energy from all available resources including those from urban environment is required. Vertical Axis Wind Turbines (VAWTs) are seen as a potential way of utilising distributed wind energy sources. Most of the research on the wind turbines constitutes performance analysis and optimisation of VAWTs, in a clean environment, using steady state approximations where the transient effects are not considered. Operations in dusty environments (such as in desserts) may change the nature of the flow field around the VAWT which could decrease its life cycle. This study is an attempt to use Computational Fluid Dynamic's based techniques to study and analyse the performance of a wind turbine under dusty environment. For this purpose, a novel modelling technique, known as Discrete Phase Modelling (DPM), has been used in the present study to introduce dust particles in the vicinity of a VAWT. The predicted results show that the instantaneous torque output of the VAWT decreases significantly in dusty environment. This abrupt change in the instantaneous torque output of the turbine may give rise to highly transient loads on the turbine's structure which may induce heavy stresses on the turbine, leading to structural failure.

2. Introduction

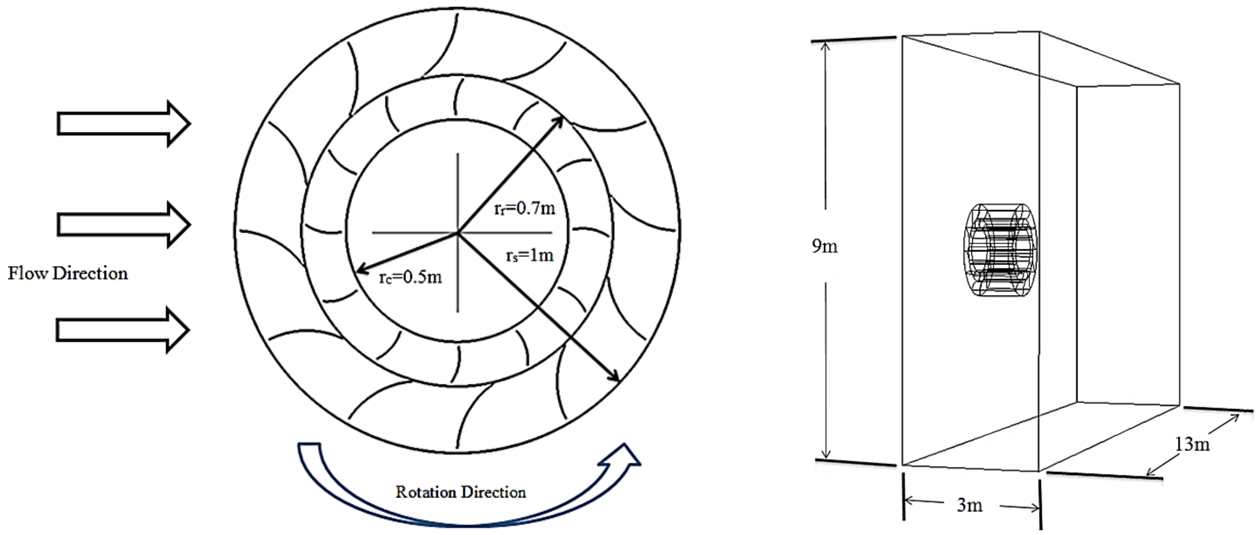
CFD based analysis is currently being employed for the aerodynamic design of wind turbines as numerical simulations offer reasonably accurate information on the fluid behaviour within various systems, assisting the engineers to obtain performance envelope of a particular design [1-10]. Published literature regarding erosion in VAWTs is severely limited. Gharali et al. [11] conducted studies examining a range of erosion characteristics on NACA profiles, in which erosion has been simulated using different length scales. Authors have found that the eroded areas usually have sharp edges. The leading edge area of the affected blades presents some indication of erosion. Hameed et al. [12] examined a number of scholarly studies on erosion and deposition, and their effects on turbomachines, as well as their association in degradation of engine performance linked to particulate matter ingestion. It has been observed that erosion on turbomachines, including wind turbines, are influenced by various factors such as particle characteristics, gas flow path, blade geometry, operating conditions and blade material. The coatings applied to the material of the components are also linked to various erosion related effects.

Erpul et al. [13] investigated the effects of wind driven rain on the erosion processes. Rain falls with a vertical velocity component; however, with the influence of wind acting on the rain, raindrops gain some degree of horizontal velocity component as well. Therefore, when the rain strikes the soil, particles shear off. The same effect occurs on the wind turbine blades. As the sand particles strike the blades, the velocity magnitude of the wind sheds material off the blade. This phenomenon must occur continuously on the same region/s of the blades for erosion to take place. Keegan et al. [14] pointed out that the unpredictable and potentially volatile operating environmental conditions present great challenges to the development in wind technology, with respect to erosion issues on the leading edge of the wind turbine blades. Rain droplets and hailstones have been identified by Keegan as a prime focus in the research area on the erosion of the wind turbine blades.

The literature review presented here has shown that erosion is serious issue in Vertical Axis Wind Turbines that causes roughness on the blades via airborne dirt, debris and insects. Erosion has been shown to degrade the performance characteristics of a VAWT significantly. A number of different strategies have been employed to analyse erosion in VAWTs, and with the advent of powerful and advanced computational methods, it has become possible to investigate erosion at microscopic levels. Hence, this study is based on the predictions from numerical simulations performed using a Computational Fluid Dynamics (CFD) based solvers.

3. Numerical Modelling of HCP Bends

A three dimensional vertical axis wind turbine model, similar to Colley [15], has been numerically created, as shown in figure 1(a). The model has 12 rotor blades and 12 stator blades. The radius of the core region r_c=0.5m whereas the radii of the stator and the rotor regions i.e. r_r and r_s are 0.7m and 1m respectively. The height of the VAWT, h=1m. Furthermore, figure 1(b) shows the flow domain of the VAWT. The length, width and the height of the flow domain are 13m, 9m and 3m respectively. These dimensions have also been taken from Colley.



(a) *(b)*

Figure 1 Geometric details of (a) VAWT (b) The Flow Domain

The mesh has been created in two different steps. Domain mesh has been controlled by global sizing function i.e. maximum size of 100mm and minimum size of 0.1mm. Stator, rotor and the core zones have been meshed for 30mm mesh sizing, whereas the rest of the flow domain has been meshed for 100mm mesh sizing.

The flow of sand particles in the flow domain, for erosion studies, is quite complicated to model as the trajectory of the sand particles while passing through the VAWT cannot be known in advance. A novel modelling technique, called Discrete Phase Model (DPM), has been used in the present study to accommodate this. According to Edwards et al. [16], the ability to predict erosion has been added to the CFD code through a network of FORTRAN subroutines. Impingement information is gathered as particles impinge the walls of the geometry. As particle trajectories are computed, this impingement information is recorded and erosion is computed using empirical relations. Particle erosion can be monitored at wall boundaries. The erosion rate is defined as:

$$R_{erosion} = \sum_{p=1}^{N\ particles} \frac{\dot{m}_p\, C(d_p)\, f(\alpha)\, v^{b(v)}}{A_{face}} \tag{1}$$

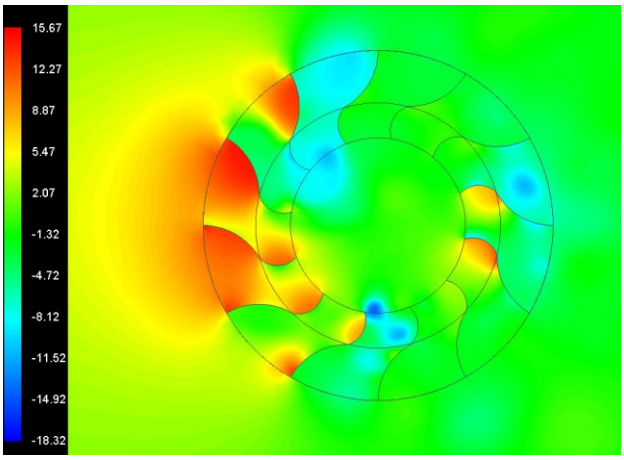
where $\dot{m}p$ is the mass flow rate of the sand particles, C(dp) is a function of sand particles' diameter, α is the impact angle of the particles with the wall face, f(α) is a function of impact angle, v is the relative particle velocity, b(v) is a function of relative particle velocity and $\dot{m}p$ is the mass flow rate of the sand particles and is considered as 1kg/sec in the present study. Aface is the area of the cell face at the wall and is computed automatically by the solver. These parameters are defined as boundary conditions to the VAWT's walls. Values of these parameters for sand eroding aluminium are given by Edwards as $C(dp)=2.388 \times 10^{-7}$ and b(v)=1.73. Aface is automatically computed by the solver, based on the mesh information.

Three dimensional Navier Stokes equations, alongwith the continuity equation, have been iteratively solved for the transient turbulent flow of air and sand particles in the vicinity of the VAWT. SST k-ω model has been chosen for the modelling of turbulence. The incident air flow velocity is 4m/sec, which is the annual average wind speed in Huddersfield, UK. Furthemrore, the Tip Speed Ratio (λ) is also kept constant at 0.4 because it represents the most common operating condition in real world practice (Colley [15]).

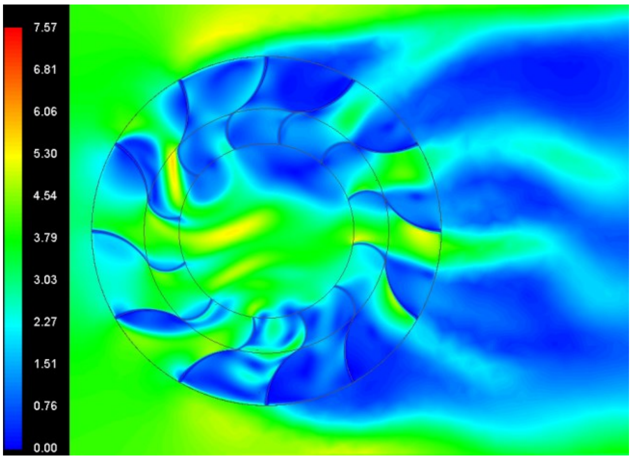
4. Results and Discussions

Figure 2 depicts the variations in the flow structure and the instantaneous torque output of the VAWT operating in a clean environment. It can be seen in figure 2(a) that the high pressure regions are either on the windward side of the VAWT, or in the vicinity of rotor blades on the leeward side of the VAWT. Similarly, the low pressure regions occur primarily on the upper and lower sections of the VAWT. Similarly, it can be seen in figure 2(b) that although the incident wind velocity is 4m/sec, it can increase upto 7.57m/sec within the VAWT. As expected, the flow velocity is high in the passages formed between stator and rotor blades, whereas it is considerable lower in the zones where there is more resistance to the flow path (such as the upper and lower sections of the VAWT). The effects of flow jets formed in the passages between the rotor and the stator blades can be noticed even within the core region of the VAWT. Furthermore, figure 2(c) depicts that when the rotor blades are inline with the stator blades, the flow smoothly propagates through the passages formed in between the blades, following the line of the blade's curvature for those pathlines that are very close to them.

Figure 2(d) depicts the variations in the instantaneous torque output generated by it in one revolution of its operation. The cyclic variations in the torque have been observed by many researchers, where the number of both positive and negative peaks are equal to the number of rotor blades of the VAWT. Each cycle (one wavelength) corresponds to the circular motion of a rotor blade from one stator blade to the next one. The average torque output has been calculated to be 7.73Nm.



(a)



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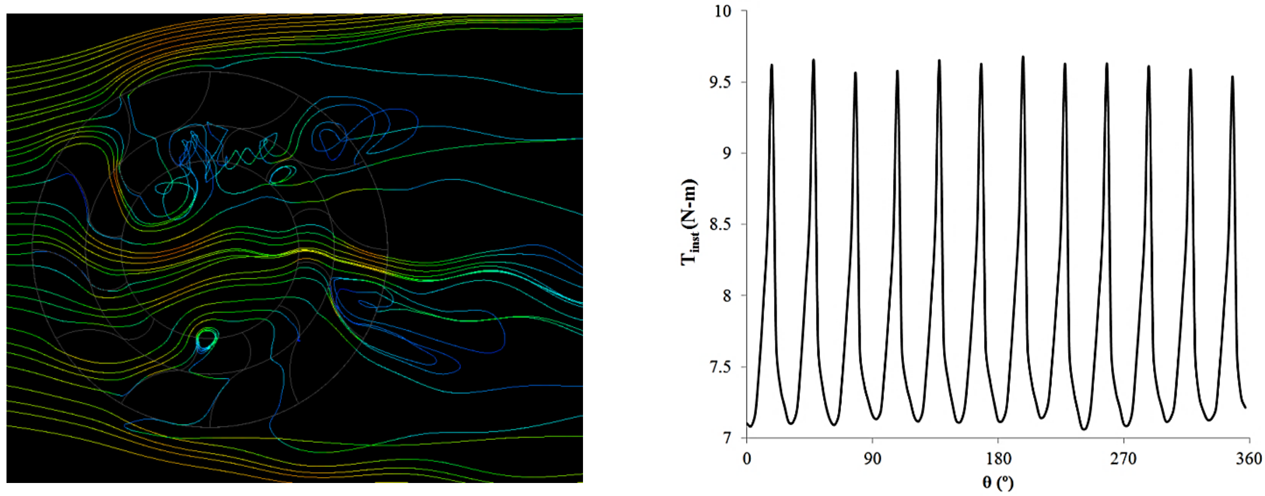
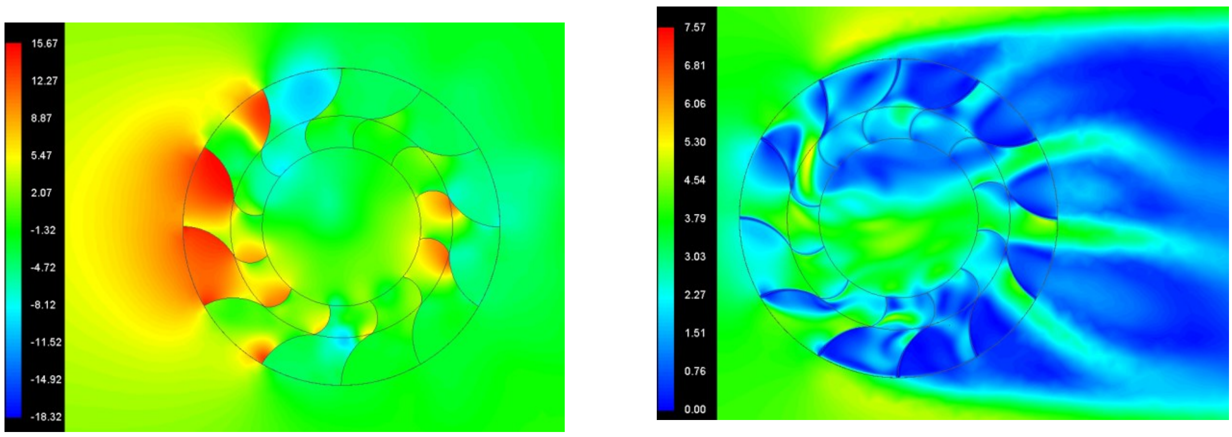


(c) *(d)*

Figure 2 Flow and performance characteristics of the VAWT in a clean environment (a) Static gauge pressure (b) Velocity magnitude (c) Flow pathlines (d) Instantaneous torque output

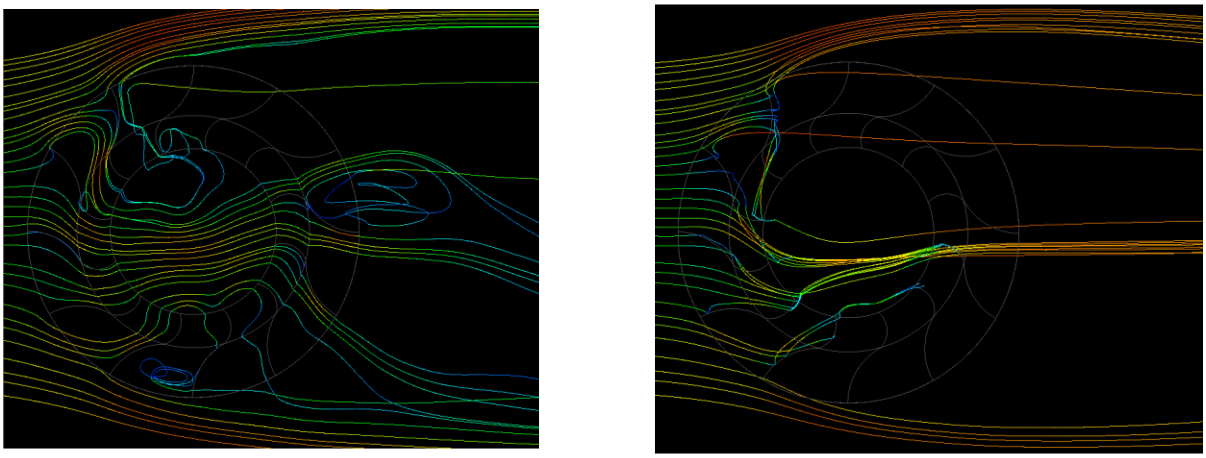
Figure 3 depicts the variations in the flow structure and the instantaneous torque output of the VAWT operating in a dusty environment. It can be seen in figure 3(a) that the high pressure regions are on the windward and leeward sides of the VAWT, whereas the low pressure regions occur primarily on the upper and lower sections of the VAWT. Similarly, in figure 3(b), the flow velocity is high in the passages formed between stator and rotor blades, whereas it is considerable lower in the zones where there is more resistance to the flow path. Comparing figures 3(a) and 3(b) with figures 2(a) and 2(b) reveals that the general trend remains the same, however, there are significant local variations in the static gauge pressure and velocity magnitude distributions.

Figure 3(c) and 3(d) depicts the path followed by the air and the sand particles respectively. In comparison with figure 2(c), it can be seen in figure 3(c) that due to the presence of sand particles in the flow domain, the path followed by air changes significantly. Furthermore, as shown in figure 3(d), that most of the sand particles enter the VAWT through the passages formed between the rotor and stator blades on the windward side of the VAWT. However, due to a number of resistances in their path (in the form of blade walls), most of the sand particles get settled on these walls, whereas some particles escape the VAWT through the passages on the leeward side of the VAWT.



(a) *(b)*

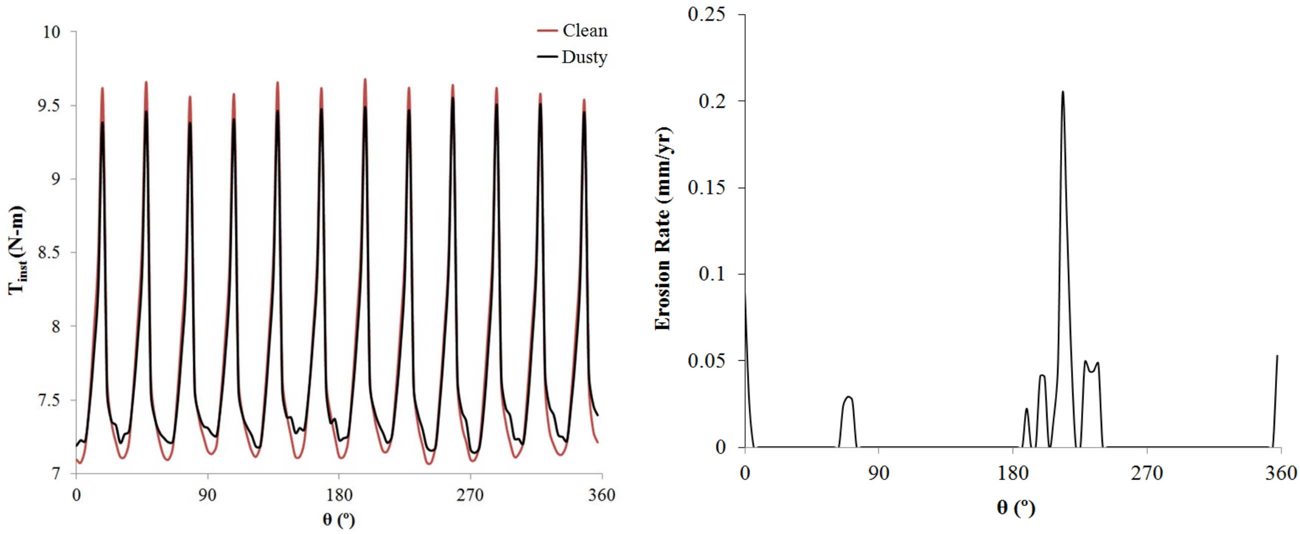
Figure 4(a) depicts the comparison of the instantaneous torque output from the VAWTs operating in clean and dusty environments, where the sand particles' diameter is 125microns. It can be clearly seen that the presence of sand particles in the flow domain degrades the performance output of the VAWT by reducing its torque generating capabilities. The average torque generated by the VAWT under dusty conditions is 0.11% less than the VAWT operating in clean environment.



(c) *(d)*

Figure 3 Flow characteristics of the VAWT in a dusty environment (a) Static gauge pressure (b) Velocity magnitude (c) Flow pathlines (d) Sand particles' tracks

In order to quantitatively estimate the effects of a dusty environment on the erosion characteristics of a VAWT, instantaneous erosion rate (in mm/yr) has been monitored on one of the rotor blades for one complete revolution of the VAWT (figure 4(b)). It can be seen that the erosion rate is highest on the rotor blades when they are either on the windward or the leeward sides of the VAWT. It has already been shown in figure 3(d) that most of the sand particles propagate through the passages formed either at the front or the rear of the VAWT, hence eroding the rotor blades. The maximum erosion rate calculated for the case under discussion is 0.2mm/yr. Furthermore, it has also been noticed that apart from the windward and leeward sides of the VAWT, the rotor blades show negligible erosion rates as the sand particles either get deflected or settles on the blades present at other locations of the VAWT.



(a) *(b)*

Figure 4 Instantaneous performance and erosion characteristics of the VAWT operating in a dusty environment (a) Torque output (b) Erosion rate

5. Conclusions

Detailed flow analysis within and in the vicinity of the VAWT operating in a clean environment has been carried out in the present study. Both qualitative and quantitative analyses show that the static gauge pressure is considerable higher on the windward and leeward sections of the VAWT, whereas it is relatively lower on the upper and lower sections. Furthermore, it has been observed that the flow velocity is high in the passages formed between stator and rotor blades, whereas it is considerable lower in the zones where there is more resistance to the flow path. Sand particles' tracks show that most of the sand particles enter the VAWT through the passages formed between the rotor and stator blades on the windward side of the VAWT. However, due to a number of blades in their path, most of the sand particles get settled on these blades, whereas some particles escape the VAWT through the passages on the leeward side of the VAWT.

6. References

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