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Effects of Sand Particle Size on the Performance Characteristics of a Vertical Axis Wind Turbine

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Abstract

Vertical Axis Wind Turbines (VAWTs) are used to harness wind energy to meet renewable energy targets. Operations in dusty environments, such as in deserts, could adversely impact on its performance output. In order to analyse this, both clean and dusty environments have been numerically simulated using Computational Fluid Dynamics (CFD) based techniques, where the dusty environments constitute of various sand particle sizes. Comparative studies between clean and dusty environments have been presented. Critical analysis of the erosion rate on a rotor blade of the VAWT has also been carried out. It has been shown that sand particles decrease the torque output of the VAWT. It has also been shown that increase in sand particle size decreases the performance of the VAWT. The results obtained have been used to develop a novel semi-empirical prediction model for the torque output of the VAWT as a function of sand particles' size.

Keywords: *Vertical Axis Wind Turbine, Computational Fluid Dynamics, Erosion Rate, Torque Coefficient*

I. INTRODUCTION

CFD based analysis assists engineers to obtain performance of a particular design since numerical simulations offer reasonably accurate information on the fluid behaviour [1-4]. The numerical study carried out by Khakpour [5] reported that the performance of wind turbines are affected by environments with sand particles . The results have been compared against uniform performance, under other less invasive and damaging conditions. Erosion due to the collision of sand particles with the blade surface, for several angles of attack, has been studied. Work by El Batsh [6] reveals that the particles smaller than 100μm stick to the surface upon impact. For larger particles, the probability of sticking depends on particle size, particle impact velocity and temperature. Keegan et al. [7] pointed out that the unpredictable and potentially volatile operating environmental conditions present great challenges to the development in wind technology, especially to control erosion issues on the leading edge of the wind turbine blades. An experimental study by Khalfallah et al. [8] on the impact of blade surface roughness due to dust accumulation revealed that with the increase of dust accumulation on the blades, the drag force on the airfoil increases, and lift force decreases. This causes a reduction in the turbine's power output. It had also been discovered that the dust particle size has significant impact on the blade's surface roughness over time. With increase in dust particles size, the power output of wind turbine decreases. Other studies, such as that of Ren et al. [9] and Salem et al. [10] have investigated the effect of dust particles' interaction with wind turbine blades' performance. One major area that needs a systematic research is the effect of multi-sized sand particles on erosion rate. With the advent of powerful and advanced computational methods, it has become possible to numerically investigate the effect of sand particle size on VAWTs. Hence, this study is based on erosion rate predictions from numerical simulations performed using a Computational Fluid Dynamics based solver.

II. NUMERICAL MODELLING

The numerical model of the VAWT is shown in figure 1. The model considered here is similar to the one studied by Colley et al. [11] and has 12 rotor blades and 12 stator blades. The height of the VAWT is 1m. This VAWT model is placed in a rectangular flow domain of length, width and height of 13m, 9m and 3m respectively. Uniform mesh elements of 30mm and 100mm size have been generated within the VAWT and the flow domain respectively. It has been observed that these mesh sizes are capable of accurately predicting the complex flow phenomena, and the erosion rate on the blades of the VAWT.

Discrete Phase Modelling (DPM) has been employed in the present study to predict the trajectory of sand particles while passing through the VAWT, in dusty environments. Particle erosion can be monitored at wall boundaries. The erosion rate is defined as [12]:

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

where $\dot{m}_p$ is the mass flow rate of the sand particles, $C(d_p)$ 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 A_{face} is the area of the cell face at the wall. Three dimensional Navier Stokes equations, along with 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 turbulence model has been chosen for turbulence modelling. The Tip Speed Ratio is kept constant at 0.4 since it represents the most common operating condition in real world practices for this device (Colley et al. [11]).

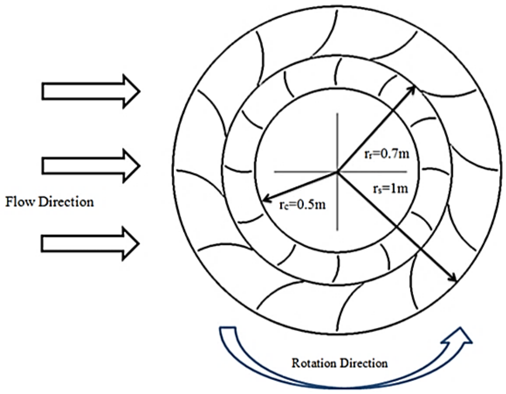
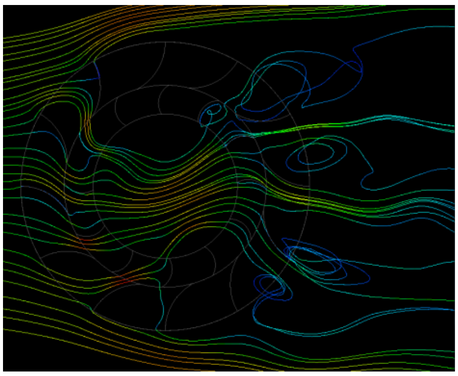


Fig.1 Geometric details of the VAWT

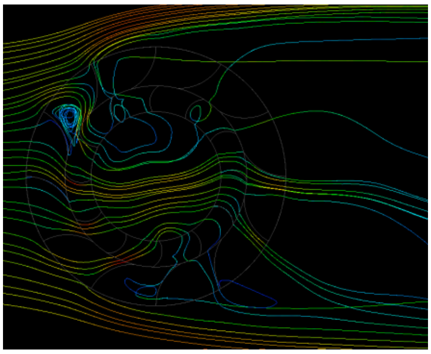
III. RESULTS AND DISCUSSION

Figures 2(a-c) depict the air flow pathlines in the vicinity of the VAWT for clean environment, dusty environment with 125microns and 500microns sized sand particles respectively. It can be seen that the air enters the VAWT through the opening formed between rotor and stator blades on windward side, follows the blades' curvature, and then exits the VAWT from the leeward passages. The main difference in these figures is the flow behaviour as sand particles of different sizes are introduced. It can be seen in figure 2(b), as compared to figure 2(a) that although the amount of air entering the VAWT remains the same, air exiting the VAWT from the leeward passages is affected when sand particles are introduced. Introduction of sand particles generates local turbulence within the flow and hence, air has been noticed to exit from the top and bottom sections of the VAWT as well.

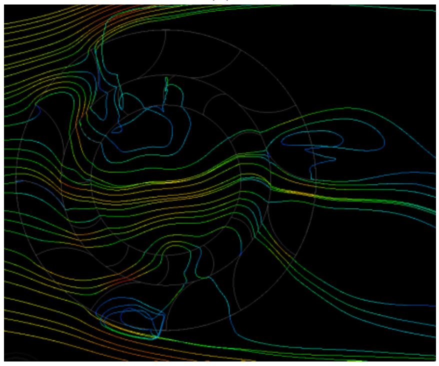


(a)

Figures 3(a-b) depict the variations in the sand particle tracks in the vicinity of the VAWT for 125microns and 500microns sized sand particles. It can be seen that majority



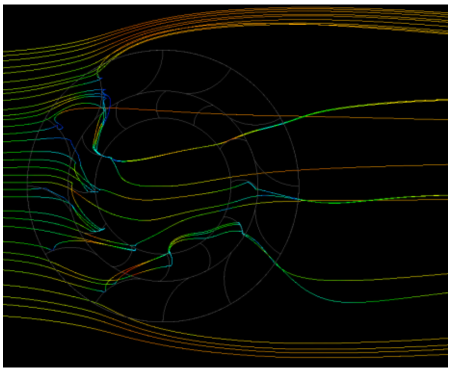
(b)



(c)

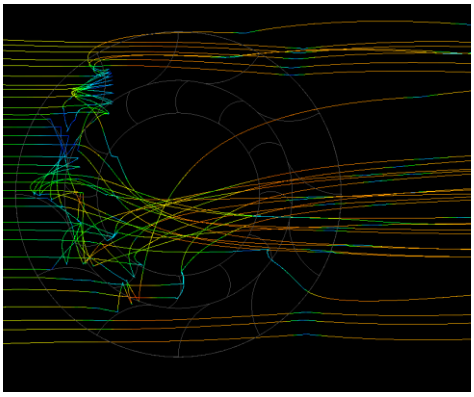
Fig.2 Air flow pathlines in the vicinity of the VAWT (a) clean environment (b) 125μm (c) 500μm

of the sand particles enter the VAWT through the opening passages formed between the rotor and stator blades on the windward side of the VAWT. However, due to a number of resistances in the flow path in the form of blade walls, a considerable amount of sand particles get settled on these walls, whereas some particles escape the VAWT through the passages on the leeward side of the VAWT. It can clearly be seen that the flow smoothly follows the opening passage between the rotor and stator, and then follows the curvature of the blades on the windward side. The primary difference in these figures is that larger sand particles strike the blades on the windward side of the VAWT and get rebounded, however, under the effect of the incident flow momentum, they are forced back towards the VAWT, where they propagates through the passages and finally exit the VAWT.



(a)

Figure 4 depicts the instantaneous erosion rates on a rotor blade for one complete revolution of the VAWT. It can be seen that as the sand particles' size increases, the erosion rate on the blades increases. Higher erosion rate is observed when the rotor blades are either on the windward or the



(b)

Fig.3 Sand particles' tracks in the vicinity of the VAWT (a) 125microns (b) 500microns

leeward sides of the VAWT. The maximum erosion rate observed for sand particles of size 500microns is 1.26mm/yr, whereas for 250microns and 125microns sized particles are 0.3mm/yr and 0.2mm/yr respectively.

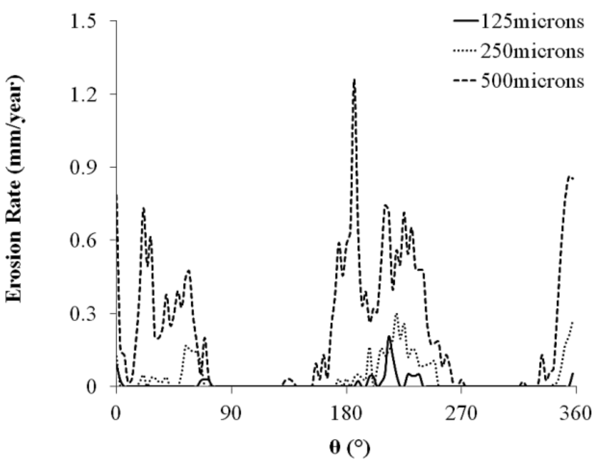


Fig.4 Instantaneous variations in the erosion rate of a rotor blade

Figure 5 depicts the instantaneous torque output of the VAWT under various environmental conditions. It can be seen that the torque coefficient variations of the VAWT are cyclic in nature, with distinct peaks, which are equal in number to the number of rotor blades of the VAWT. It has also been observed that as the sand particles are introduced into the flow domain, the torque coefficient of the VAWT decreases. Furthermore, as the sand particle's size increases, the torque coefficient of the VAWT decreases. This information can be used to develop a novel semi-empirical prediction model for the torque coefficient of the VAWT, as follows:

$$C_{T,Total} = C_{T,Clean} - C_{T,Dusty} \quad (2)$$

$$C_{T,Clean} = 0.066\,\mathrm{Sin}(2\pi ft + 10.2) + 0.425 \quad (3)$$

$$C_{T,Dusty} = \frac{0.0003}{\left(\frac{d}{R}\right)^{0.383}}\,\mathrm{Sin}(2\pi ft + 10.2) + 0.0036\ln\left(\frac{d}{R}\right) + 0.0323 \quad (4)$$

where d is the diameter of the sand particles, R is the radius of the rotor blades, f is the frequency of peaks in torque coefficient.

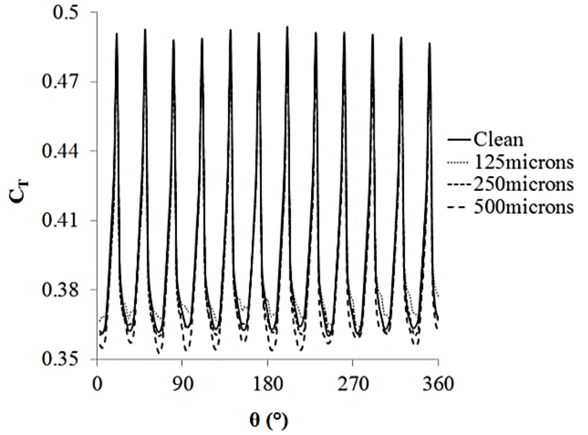


Fig.5 Instantaneous torque output of the VAWT operating under various environmental conditions

IV. CONCLUSIONS

The present study provides a detailed flow analysis in the vicinity of the VAWT operating in both clean and dusty environments. Both qualitative and quantitative analyses show that introduction of sand particle creates local turbulence in the flow field, and degrades the performance output of the VAWT. This has been demonstrated in terms of the erosion rate and the torque coefficient of the VAWT. A novel semi-empirical correlation has been developed for the performance of the VAWT that takes into account the sand particles' size.

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