Experimental and Numerical Study of Erosion Wear of Fan Blades in Microgrid

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Abstract. As one of the most important components of wind turbines, the fan blade is prone to erosion being exposed to multiphase flow environment, which affects the operation efficiency of wind turbines. In order to reduce the loss caused by the erosion of the fan blade, the erosion rate tests of the fan blade were carried out in this paper. The relevant function values of the simulation mathematical model were calculated from the test results, which were verified by a simplified two-dimensional case. Additionally, a numerical simulation of the three-dimensional full-size gas-solid two-phase flow around the fan blade was conducted, and then the variations of a single blade erosion rate with different wind speeds, sand sizes and impact angles were studied. The results showed that the sample erosion rate was increased with wind speeds and impact angles. The blade tip region was the most susceptible area to erosion, of which protection should be strengthened.

1. Introduction

With the rapid advancement of science and technology, the global energy demand is increasingly rising, and the development of renewable energy has become an inevitable trend of sustainable development in countries around the world. The new energy microgrid can integrate multiple renewable energy sources (wind energy, solar energy, etc.), making it feasible to alleviate the non-renewable energy shortage problem and deal with air pollutions. Wind power, as an important part of the new energy microgrid, plays a significant role in the development of the new energy revolution. The fan blade is one of the most important components of the wind turbine, the performance of which affects the operational efficiency of the wind unit. However, the blade in engineering is exposed to multiphase flow environment and prone to erosion after long-term operation, which will ultimately reduce the operational efficiency of wind turbines.

In order to reduce the loss caused by the erosion of the fan blades, a large amount of studies on this phenomenon have been carried out across the world over decades. Ou et al.[1] and Qin[2] designed a set of solid particle erosion test system respectively, and the results indicated that the sample erosion rate was proportional to the flow velocity. Chen[3] utilized the high-speed jet test method to investigate the erosion of the fan blade surface, and calculated the blade erosion rate by applying the weight-loss method. Suresh et al.[4] conducted erosion wear tests on glass fiber composite materials to study the effects of parameters such as particle shape and impingement angle on composite materials. Gharali[5] simulated the erosion wear at the leading edge of the blade, focusing on the effect of the drop in lift on the performance of the wind turbine. Dai[6] used the numerical analysis method of the control phase to
calculate the erosion parameters of solid particles and simulate the erosion rate distribution on the surface of the steam turbine nozzle.

In general, although a significant amount of work on erosion phenomenon around the world has been done, there is still a lack of adequate exploration of the erosion rate of different parts in the fan blade and the law between various influencing factors. Moreover, most of the simulation model-related parameters use default values. In this paper, the relevant function values in the numerical model are obtained through the experimental results of the sample with the subsequent correction to the mathematical simulation model.

2. Erosion wear test

2.1 Test facility
In this study, the nozzle erosion test device was selected for testing, which could accurately simulate the situation of sand hitting the fan blades. Figure 1 shows the solid particle erosion test bench, which consists of a gas supply module, a sand supply module, an erosion module and a sand recovery module. Among them, an L-18.5 type linghein air compressor was used in the air supply module to provide compressed air with a pressure value of about 0.8 Mpa, and the wind speed was adjusted by the pressure regulator valve. The sand supply module contained a sand storage bin and a sand discharge regulating valve, which controlled the sand velocity together with the pressure regulator valve. The erosion module was a cube box made of transparent acrylic board with a size of 30 mm × 30 mm × 30 mm, within which a groove with a size of 20 mm × 20 mm × 3 mm was employed to place the sample. The function of the sand recovery module under the erosion module was to recover the sands after the test was completed.

![Figure 1. Test bench for erosion of solid particles.](image)

2.2 Test method and process of solid particle erosion
In this test, the weight loss of the test sample was considered as the criterion of the amount of sample erosion. The equation of erosion rate is written as

\[ \varepsilon = \frac{\Delta M}{A_{\text{face}} \times t} \]  

\[ A_{\text{face}} = A \times \sin \alpha \]  

with \( \varepsilon \) the sample erosion rate, \( \Delta M \) the weight loss of the test sample, \( A_{\text{face}} \) the area of the cell face at the wall, \( t \) the erosion time, \( A \) the surface area of the sample and \( \alpha \) the particle impact angle.

The test procedure could be summarized as follows: firstly, the sample was cleaned in an ultrasonic cleaner for one minute and dried to ensure the accuracy of sample weight recorded subsequently. After recording the weight, the sample was placed on the groove within the erosion module and the sands were poured into the sand storage bin. Then, the air compressor was activated, and the wind speed at the nozzle port was measured by the Pitot tube, which could be adjusted by the pressure regulator valve to obtain different initial sand speeds. And afterward, the distance between the nozzle port and the center of the sample was set to 10mm and then the test was conducted for ten minutes. Lastly, the processes in the first step were repeated for sample after test, including cleaning, drying, weighing, and recording. Moreover, in order to ensure the accuracy of the test results, five repeated tests were performed for each condition, and the average weight loss for five tests was considered as the sample weight loss, which was substituted into equation (1) to obtain the erosion rate.
3. Theoretical model of erosion

In the FLUENT discrete phase simulation model, the solid particle erosion rate is defined as [7-10]:

$$R_{\text{erosion}} = \sum_{p=1}^{N_{\text{particles}}} \frac{m_p C\left(d_p\right) f\left(\alpha\right) v_p b\left(v_p\right)}{A_{\text{face}}},$$

(3)

where $R_{\text{erosion}}$ is the sample erosion rate per unit area, $N_{\text{particles}}$ is the number of solid particles hitting the sample per unit area, $m_p$ is the mass flow rate of the solid particles, $C\left(d_p\right)$ is a function of the solid particle diameter, $f\left(\alpha\right)$ is a function of the particle impact angle, $v_p$ is the relative particle velocity, $b\left(v_p\right)$ is a function of the relative particle velocity.

In this test, $m_p$ was equal to the ratio of the total mass of solid particles to the erosion time, which was about $8.333\times10^{-4}$ kg/s. The rest of the functions, e.g. $b\left(v_p\right)$, $f\left(\alpha\right)$ and $C\left(d_p\right)$, could be calculated based on the test results of the sample with the subsequent correction to the mathematical simulation model.

3.1 The velocity function of solid particles

When the sand speed changes while the other conditions remain constant, equation (3) is transformed into

$$\frac{R_1}{R_2} = \frac{v_1 b\left(v_p\right)}{v_2 b\left(v_p\right)},$$

(4)

in which the subscripts 1 and 2 represent different tests. After comparing the sample erosion rates in different tests, the results displayed that when the velocity was $7.9 \sim 12.8$ m/s, $b\left(v_p\right) = 0.4898$. Similarly, when the velocity was in the range of $12.8 \sim 17.6$ m/s, $b\left(v_p\right) = 0.4604$, and when the velocity was in the whole range of $7.9 \sim 17.6$ m/s, $b\left(v_p\right) = 0.4781$. Finally, $b\left(v_p\right) = 0.4781$ was selected and applied to the numerical model.

3.2 The impact angle function of solid particles

The working condition of 90 degree impact angle was taken as the standard of impact angle for material erosion, and the impact angle function $f\left(\alpha\right)$ was defined as a dimensionless number and set to one. Thus, the other impact angle functions are expressed as

$$\frac{R_s}{R_n} = \frac{f\left(\alpha\right)_n \times \sin \alpha_n}{f\left(\alpha\right)_n \times \sin \alpha_s},$$

(5)

where $R_s$ is the erosion rate with the impact angle of 90 degree, $R_n$ and $f\left(\alpha\right)_n$ represent the sample erosion rates and the impact angle functions of the tests with impact angles of 15, 30, 45, 60 degree. The results of impact angle functions can be found in table 1.

| Serial number | $\alpha$(°) | $f\left(\alpha\right)_n$ |
|---------------|-------------|-----------------|
| 1             | 15          | 0.6816          |
| 2             | 30          | 0.7462          |
| 3             | 45          | 0.8009          |
| 4             | 60          | 0.8416          |
| 5             | 90          | 1.0000          |

Table 1. The impact angle function of solid particles.
3.3 The size function of solid particles

On the basis of the previously obtained functions, the sand particle size functions were calculated by averaging the sand particle sizes in different intervals. The results are shown in table 2.

\[
C(d_p) = \frac{R \times A_{\text{size}}}{m_p \times f(\alpha)v_p^4}.
\]

Table 2. The size function of solid particles.

| Serial number | Size of sand (mm) | \(C(d_p)\) |
|---------------|-------------------|------------|
| 1             | 0.070-0.150       | 1.1324×10^{-6} |
| 2             | 0.150-0.210       | 1.6550×10^{-6} |
| 3             | 0.210-0.400       | 1.4808×10^{-6} |
| 4             | 0.400-0.850       | 1.2195×10^{-6} |

3.4 Validation of the theoretical model

In order to ensure the accuracy of the previously calculated functions, a validation case was needed first. In the validation case, the computational domain was a rectangle with a size of 250 mm × 200 mm, within which a two-dimensional sample model with a size of 60 mm × 5 mm was placed, which was 100 mm away from the nozzle port with a size of 18 mm × 3.6 mm. The \(k-\varepsilon\) standard model was used for turbulence model, the discrete phase model was selected for the gas-solid two-phase flow, and the density-based implicit solver was applied to solve the governing equations. Air represented the gas phase, with a density of 1.225 kg/m³ and a viscosity of 1.789×10^{-5} kg/ms, while sands represented the solid phase, with a density of 2650 kg/m³ and with a volume fraction in air of 5×10^{-7}.

Figure 2 (a), (b), (c) display the variation of erosion rate in the test and simulation results with wind speed, particle size, and impact angle, respectively. It is observed that the average erosion rates obtained by simulation under different conditions were in good agreement with those in experimental results, while the maximum erosion rates in numerical results were slightly different from those in experimental results. The complex erosion process of solid particles and the error from the test environment were likely part of the reasons for the difference. But on the whole, the erosion rates obtained by simulation were basically consistent with the test results, which validated the accuracy of the functions.

Figure 2. Comparison of erosion rate in experimental and numerical results under different conditions: (a) wind speeds; (b) particle sizes; (c) impact angles.

4. Numerical simulation of fan blades

The gas-solid two-phase flow erosion on the fan blade is an extremely complicated phenomenon to simulate. In order to simplify the simulation process, the following assumptions were introduced: (a) The solid phase was treated as dilute phase. (b) Solid particles were regarded as homogeneous spheres with the same density, which were primarily affected by fluid drag, gravity and buoyancy. (c) The fluids in the computational domain were considered as a single gas-phase.
4.1 Numerical model
Figure 3(a) displays the three-dimensional full-scale geometric model of the fan blade with the propeller radius of 26 m, the maximum chord length of 2.3 m, the minimum chord length of 0.3 m, and the maximum blade twist angle of 12°. The three-dimensional full-scale mesh of a single blade and the local mesh refinement are shown in figure 3(b), 3(c), respectively. The computational domain was a cuboid with a size of 20 m × 43.5 m× 21.5 m, in which 1.765 million structured grids were generated. The physical properties of the gas-solid two-phase and the turbulence model were the same as those in the previous validation case.

4.2 Analysis of numerical results

4.2.1 The effect of wind speed on erosion. Figure 4 shows the distributions of blade erosion rate for different wind speeds when the sand size range is 0.15 mm to 0.21 mm and the impact angle is 45°. It was observed that the blade erosion area gradually expanded with the inlet wind speed. The faster the inlet wind speed, the higher the sand kinetic energy peak, and therefore the surface stress of the sample was increased and the sample erosion rate was aggravated.

4.2.2 The effect of sand size on erosion. Figure 5 exhibits the distributions of blade erosion rate for different sand sizes when the inlet wind speed is 12.9 m/s and the impact angle is 45°.
It was observed that there was no significant difference in blade erosion rate under different working conditions. Nevertheless, the erosion region spread out continuously and the blade tip erosion was more serious than blade root erosion. Thus, it was noted that the protection of the blade tip region should be strengthened.

4.2.3 The effect of impact angle on erosion. Figure 6 illustrates the distributions of blade erosion rate for different impact angles when the sand size range is 0.15 mm to 0.21 mm and the inlet wind speed is 12.8 m/s. It was noted that as the impact angle increased, the normal stress on the sample surface and the erosion rate gradually rose, while the tangential stress decreased accordingly. Therefore, in order to alleviate the erosion of sands on the fan blades, the blades should be at a certain angle to the wind direction.

5. Conclusion
In this paper, the erosion rate tests of the fan blade were conducted. Furthermore, the correlation functions in the mathematical simulation model were calculated based on these results and verified by a simplified two-dimensional case. In addition, a numerical simulation was performed on the three-dimensional full-scale gas-solid two-phase flow around the fan blade to analyze the erosion rate distributions at different positions of the blade.

Acknowledgments
Project supported by the National Key Research and Development Program of China (Grant No. 2017YFF0210700).

References
[1] Ou, G.F., Rao, J., Zhang, L.T., et al. (2012) A new solid particle erosion experiment system driven by shock wave. Tribology, 32: 466-471.
[2] Qin, L. (2016) Research and design on erosion experimental apparatus with liquid-solid two-
phase flow. Xi'an: Xi'an Shiyou University.

[3] Chen, Q.P. (2014) Wear Test Research on Fan Blade Materials. Fluid Machinery, 42: 12-15.

[4] Suresh, A., Harsha, A.P., Ghosh, M.K. (2009) Solid particle erosion studies on polyphenylene sulfide composites and prediction on erosion data using artificial neural networks. Wear, 266: 184-193.

[5] Gharali, K., Johnson, D.A. (2012) Numerical modeling of an S809 airfoil under dynamic stall, erosion and high reduced frequencies. Applied Energy, 93: 45-52.

[6] Dai, L., Yu, M.Z., Dai Y.P. (2007) Nozzle passage aerodynamic design to reduce solid particle erosion of a supercritical steam turbine control stage. Wear, 262: 104-111.

[7] Zhang, Y.I. (2006) Application and improvement of computational fluid dynamics (CFD) in solid particle erosion modeling. Tulsa: The University of Tulsa.

[8] Ji, H., Zhang, S.W., Liu, X.Q., et al. (2018) Effect of solid particles on erosion wear of prestage of jet deflector servo valve. Journal of Lanzhou University of Technology, 44: 44-48.

[9] Cui, L., Ran, Y.N., Li, Z. (2017) Development and prospect in particle erosion calculation models. Total corrosion control, 31: 52-54.

[10] Zhang, L., Wang, S.X., Peng, Z.G., et al. (2014) Model analysis of ball seat for horizontal open hole fracturing. China Petroleum Machinery, 42: 76-79.