Numerical Investigation on the Wear Characteristics of Vertical-Axis Wind Turbine Blades in a Sand-Dust Environment

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Abstract

To address the abrasion of wind turbine blades caused by continuous sand and dust impacts during operation, a coupled numerical simulation method combining computational fluid dynamics (CFD) and the discrete element method (DEM) was used to investigate abrasion induced by the interaction between wind-blown sand particles and wind turbine blades. Compared with traditional pure CFD numerical simulation methods, the CFD-DEM coupling method can accurately account for interactions between particles and between particles and wind turbine blades, while also considering the actual geometric shapes of real wind-blown sand particles. In addition, inlet fluctuating wind speed was generated using the large eddy simulation model, allowing the fluctuating characteristics of wind speed in actual sandy weather to be fully considered. Based on published experimental data in the literature, the results calculated using the turbulence model and abrasion model were numerically validated, and the effects of parameters such as inlet fluctuating wind turbulence intensity, particle mass concentration, and particle sphericity on blade abrasion were further investigated. The results show that the average wear depth gradually increases with increasing inlet fluctuating velocity and turbulence intensity. In addition, an increase in the mass concentration of wind-blown sand particles leads to simultaneous increases in both the maximum and average wear depths of the blade. As particle sphericity increases, both the average and maximum wear depths decrease. Notably, when particle sphericity exceeds 0.7, the average wear depth shows only minor variation with further increases in sphericity. The abrasion rate was calculated and the relationship curve between abrasion rate and particle sphericity was fitted, showing an approximately -1.32 power-law relationship between abrasion rate and particle sphericity. Analysis of abrasion data under the influence of different parameters indicates that the mass concentration of wind-blown sand particles has the most significant effect on the abrasion of wind turbine blades. The simulation results can provide guidance for predicting and preventing abrasion in the actual operation of wind turbine blades.

Full Text

Numerical Investigation on the Wear Characteristics of Vertical-Axis Wind Turbine Blades in a Sand–Dust Environment

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Abstract: To solve the problem of blade wear caused by the continuous impact of sand and dust during the operation of wind turbines, a coupled numerical simulation method combining computational fluid dynamics (CFD) and the discrete element method (DEM) was adopted to study the wear caused by the interaction between wind-sand particles and wind turbine blades. Compared with the traditional pure CFD numerical simulation method, the CFD-DEM coupling method can accurately account for the interactions between particles and between particles and wind turbine blades, and can also consider the true geometric shapes of actual wind-sand particles. In addition, a large-eddy model was used to generate inlet pulsating wind speed, so that the pulsation characteristics of wind speed in an actual wind-sand atmosphere could be fully considered. Based on experimental data published in the literature, the results calculated by the turbulence model and the wear model were numerically verified. The effects of parameters such as inlet pulsating-wind turbulence intensity, particle mass concentration, and particle sphericity on blade wear were then investigated. The results show that, as the inlet pulsating wind speed and turbulence intensity increase, the average wear depth gradually increases. In addition, an increase in the mass concentration of wind-sand particles leads to simultaneous increases in both the maximum and average wear depths of the blade. As particle sphericity increases, both the average and maximum wear depths decrease. It is noteworthy that when the particle sphericity exceeds 0.7, as the sphericity further increases, the average wear depth changes only slightly. The wear rate was obtained through calculation, and the relationship curve between the fitted wear rate and particle sphericity was established; in the fitted curve, the wear rate and particle sphericity show an approximately -1.32 exponential relationship. By analyzing the wear data under the influence of different parameters, it can be concluded that the mass concentration of wind-sand particles has the most important influence on the wear of wind turbine blades. The simulation results can provide certain guidance for wear prediction and prevention in the actual operation of wind turbine blades.

Keywords: wind power generation; wear; crosswind; pulsating wind speed; discrete element

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Numerical investigation on the wear dynamics of vertical wind turbine blades in sand and dust environment

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Abstract: In order to solve the problem of wear of wind turbine blades caused by the continuous impact of sand and dust during operation, a coupled numerical simulation method of computational fluid dynamics (CFD) and discrete element method (DEM) was used to study the interaction between sand particles and

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wind turbine blades based on the literature. Compared with traditional pure CFD-based numerical simulation methods, the CFD-DEM method used in this study can accurately consider the interaction between particles and particle/wind turbine blades, and can also consider the true geometry of actual sand grains. In addition, this study uses a large eddy model to generate inlet pulsating wind, which can fully consider the pulsating characteristics of wind speed in actual wind and sand weather. Based on existing experimental data in the literature, this study numerically verified the results calculated by the turbulence model and abrasion model, and then discussed the influence of parameters such as inlet pulsating wind turbulence intensity, particle mass concentration, and particle sphericity on blade abrasion. Numerical simulations are used to analyze the influence of parameters such as inlet turbulent wind intensity, particle mass concentration, and particle sphericity on blade wear. The research results indicate that with an increase in the turbulent intensity of the inlet pulsating wind, the average wear depth gradually increases. Furthermore, an increase in the concentration of wind-blown sand particles leads to simultaneous increases in both maximum and average wear depths of the blades. As the sphericity of particles increases, both average and maximum wear depths decrease. It is noteworthy that when the sphericity of particles exceeds 0.7, further increases in sphericity result in minimal changes in the average wear depth. The erosion rate is calculated and fitted, with the exponent of sphericity in the fitted equation approximating -1.32. By analyzing the wear data under the influence of different parameters, it can be concluded that the mass concentration of sand particles has the most significant impact on the abrasion of wind turbine blades. The simulation results can provide certain guidance for the prediction and prevention of wear of wind turbine blades in the actual process.

Key words: wind power; wear; gust; turbulent wind speed; DEM

Against the broad background of "dual carbon" and "circular economy," "carbon peaking and carbon neutrality,"as an important strategy guiding China's sustainable development, has made research related to clean energy a current hotspot. As a principal means of producing clean energy, wind power generation has also received increasing attention. However, in wind–sand environments, abrasion caused by sand particles is a major challenge facing the wind-power industry, and is also an important problem encountered in the operation of vertical-axis wind turbines. Existing studies have shown that the impact of sand particles brings serious abrasion problems to wind turbine units, resulting in high maintenance and repair costs, as well as safety problems and low power-generation efficiency[^1]. Sand-particle erosion depends on the material properties of the blade surface (size, shape, hardness, density, elastic modulus, etc.) and on conditions such as impact velocity, impact angle, temperature, and time[^2]. Therefore, clarifying the mechanism and characteristics of sand-particle erosion of wind-turbine blades and adopting targeted preventive measures are of great significance for practical engineering.

At present, experimental studies on impact abrasion of wind-turbine blades in China are relatively few, and most work is based on numerical simulation. Gao Jin et al.[^3] simulated different degrees of abrasion of wind-turbine blades caused by wind–sand particles, and found that particles with larger diameters collide with the blade wall; whereas small particles, because gravity is small, follow the air flow around the blade and cause severe scratching, with the wear rate at the blade leading edge produced by wind–sand impact and extrusion. Li Deshun et al.[^4–^5] established a three-dimensional wind-turbine model to study the influence of particle diameter on surface wear of blades. The results showed that when the particle diameter is small, most particles follow the airflow, and only a small amount collide with the blade and cause abrasion. As the particle diameter increases, gravity and inertia increase; after rebound, the particle trajectories separate completely from the fluid and collide more intensely with the blade, causing serious surface wear. Hao Fuhong et al.[^6–^8] conducted gas–solid two-phase erosion experiments on steel-structure coatings. By changing sand-particle mass and jet velocity, they found that the erosion amount increases with increases in particle mass and jet velocity. They also verified the coating erosion formula, providing a basis for actual material structures. Wang Yan[^9] systematically analyzed three different types of wind-turbine wear—pit erosion, point erosion, and spalling erosion—established geometric models separately, simulated the effects of the three wear types on the aerodynamic performance of an S809 airfoil blade, calibrated the erosion wear coefficient in the numerical experiments, and proposed a rapid method for calculating the influence on aerodynamic performance. Wang Long et al.[^10], targeting the problem of large water droplets impacting an airfoil wall, introduced the surface-tension coefficient and wall contact angle, and used the level-set method to study the process of droplet impact on the airfoil from a microscopic perspective. The numerical simulation results showed that aerodynamic force and surface tension in a low-speed environment are the main factors affecting droplet deformation.

Abroad, Gharali et al.[^11] conducted research and analyzed a series of erosion characteristics on a NACA airfoil, using different length scales for erosion simulation. The study found that the eroded regions usually have sharp edges and show obvious features in the leading-edge region of the blade.

phenomena. Hameed et al.[12] also conducted many academic studies on erosion and deposition, exploring their effects on wind turbines and their relationship with the degradation of starting performance associated with sand-particle ingestion. According to observations, erosion on wind turbines is affected by many factors, such as particle characteristics, gas-flow paths, blade geometry, operating conditions, and blade materials. The surface coating materials applied to blades also directly affect relevant parameters such as erosion rate and erosion depth. López et al.[13] pointed out that unpredictable and unstable operating environments pose great challenges to the development of wind-power technology, especially the erosion problem at the leading edge of wind-turbine blades. At present, raindrops, sand particles, and hail have mainly been identified as the principal focuses in the research field of wind-turbine blade erosion. Erpul et al.[14] studied the influence of raindrops on the blade erosion process. Rainfall has a vertical velocity component; however, owing to the effect of wind on rain, raindrops also acquire a certain horizontal velocity component. Therefore, when rainwater impacts the soil, particles detach. The same effect also occurs on wind-turbine blades. When sand particles strike a blade, the energy carried by the sand particles causes the coating material to detach from the blade. This phenomenon must occur continuously in the same region of the blade before erosion can take place. Harsha et al.[15] studied the erosion behavior of composite materials such as epoxy resin, bidirectional glass-fiber-reinforced epoxy resin, and nonoriented carbon-fiber-reinforced epoxy resin. They found that bidirectional glass-fiber-reinforced epoxy composites have higher erosion resistance than unidirectional glass-fiber-reinforced epoxy composites, and characterized the erosion behavior of composite materials used as coating materials for wind-turbine blades. Sareen et al.[16] found that leading-edge erosion of blades causes a substantial decline in blade performance and a large increase in drag; meanwhile, an increase in drag implies a significant loss of lift, and lift is a key parameter determining the power generation of wind turbines.

This study uses the CFD-DEM (computational fluid dynamics–discrete element method) approach to numerically simulate the erosion behavior caused by wind-sand particles impacting the blades of a vertical-axis wind turbine. Compared with traditional CFD methods, the advantages of CFD-DEM mainly include: it supports the introduction of particle models, so that the simulated particle shapes are closer to real particle shapes; it can consider collisions between particles and between particles and blades; it can simulate the interaction between particles and the flow field; and it can track the motion trajectory of individual particles in the flow field and calculate the fluid force they experience. The numerical simulation mainly consists of three parts: flow-field simulation, particle tracking, and erosion-rate equation calculation. Among these, the principal part affecting the accuracy of the calculation results is the erosion-rate equation calculation. The study mainly analyzes the influence laws of pulsed wind speed, dust-particle mass concentration, and sphericity on blade erosion depth and erosion rate under different turbulence intensities at the flow-field inlet. The main purpose of the study is to provide a certain reference basis for erosion prediction and prevention for vertical-axis wind turbines operating in wind-sand environments.

1 Methods and Models

1.1 CFD-DEM Governing Equations

As the continuous phase in CFD-DEM coupled computation, fluid air is solved under the Eulerian framework. The unsteady incompressible Navier–Stokes equations are applied to solve the flow field, and the governing equations are as follows.

Continuity equation

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \frac{\partial}{\partial_j}(\alpha_f \rho_f u_j) = 0 \qquad (1)$$

Momentum equation

$$\frac{\partial}{\partial t}(\alpha_f \rho_f u_i) + \frac{\partial}{\partial x_j}(\alpha_f \rho_f u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\alpha_f \mu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \alpha_f \rho_f g + F_s \qquad (2)$$

where: ρ_f is the fluid density; u is velocity; p is pressure; u_{eff} is the mixed viscosity; g is the gravitational acceleration; F_s is the interaction term between particles and fluid; and α_f is the fluid volume fraction in each cell, also called the porosity or void fraction. Assuming that the centers of all particles are located in the selected computational cell, it can be estimated by the following equation:

$$\alpha_f = 1 - \sum_{i=1}^{n} V_{p,i}/V_{\text{cell}} \qquad (3)$$

where: n is the number of particles in the selected cell; $V_{p,i}$ denotes the volume of particle i in the computational cell; and V_{cell} denotes the grid volume.

To improve the solution accuracy of turbulent vortices and generate a pulsating wind-speed inlet, the turbulence model selected is large eddy simulation (large eddy simulation, LES). LES separates large-scale vortices from small-scale vortices by means of a filter function. Large-scale vortices are directly simulated, while small-scale vortices are filtered by the filter function. This is not an average in the time domain, but an average in the spatial domain. The filtered velocity field $\bar{U}(x,t)$ can be obtained from Eq. (4). This model was first used in engineering by the atmospheric scientist Uchida et al.[17].

$$\bar{U}(x,t) = \int_{\Omega} G(r,t)\, U(x-r,t)\, dr \qquad (4)$$

where: Ω represents the entire flow domain; $G(r,t)$ is the filter function, which satisfies the normalization condition

$$\int_{\Omega} G(r,t)\, dr = 1 \qquad (5)$$

To reduce the occupation of computational resources, the filter function considers only the simplest case, namely that the filter function is uniform in all directions and independent of x. Suppose that $U(x)$ is a scalar function on $-\infty \leq x \leq +\infty$; it is easy to extend it to three dimensions. Using the filter function $G(r)$, which is uniform in all directions, the filtered velocity field is

$$U(x) = \int_{-\infty}^{+\infty} G(r)U(x-r)\, \mathrm{d}r \qquad (6)$$

Selecting the box filter function (Box Filter), $\overline{U}(x)$ is obtained by averaging $U(x')$ over $x - \frac{1}{2}\Delta \leq x' \leq x + \frac{1}{2}\Delta$. The box filter function is expressed as follows:

$$G(r) = \sqrt{\frac{6}{\pi\Delta^2}} \exp\left(-\frac{6r^2}{\Delta^2}\right) \qquad (7)$$

where Δ is the filter scale. Each filter function has a corresponding length unit Δ; generally, an eddy whose scale is larger than Δ is regarded as a large eddy.

The box filter function is a Gaussian distribution with mean 0 and variance $\sigma^2 = 1/12\Delta^2$. The value of σ^2 is determined from its second moment,

$$\int_{-\infty}^{+\infty} r^2 G(r)\, \mathrm{d}r = 1/12\Delta^2,$$

so as to remain consistent with the box filter function.

Wind-sand particles are solved as a discrete phase under a Lagrangian framework. Newton’ s second law and the soft-sphere model are used to describe particle motion. The translational and rotational motions of particles are obtained from the Newton equations:

$$m_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} = f_{p,i} + m_{ig} + \sum_{j=1}^{k_i} \left(f_{c,ij} + f_{d,ij}\right) \qquad (8)$$

$$I_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} = \sum_{j=1}^{k_i} \left(T_{c,ij} + T_{r,ij}\right) \qquad (9)$$

where m_i, I_i, v_i, and ω_i denote, respectively, the mass, moment of inertia, translational velocity, and angular velocity of the mass point; $f_{p,i}$ and m_{ig} denote, respectively, the force exerted by the fluid on the particle and the gravitational force acting on the particle; $f_{c,ij}$ and $f_{d,ij}$ denote, respectively, the constant force and damping force between particles or between a particle and the wall. The torque between particles or between a particle and the wall consists of two parts: $T_{c,ij}$ is the contact torque, and $T_{r,ij}$ is the rolling-friction torque. The contact model between particles as well as between particles and the wall is selected as the Hertz-Mindlin (no-slip) contact model [18].

1.2 Wear Model and Pulsating-Velocity Generation Method

The wear mechanism is complex and involves many factors. A universal wear model that considers all factors does not yet exist. At present, most classical wear models are established from empirical formulas, and these models contain different units of wear rate. The Oka wear model [19 − 20] considers the effects of particle diameter, impact velocity, impact angle, and wall Vickers hardness on the wear loss. This model has many parameters and is relatively comprehensive; therefore, it has been widely applied in various wear predictions. Its equation can be expressed as

$$E(\alpha) = E_{90} g(\alpha) \qquad (10)$$

$$E_{90} = K(aH_v)^{k_1 b} \left(\frac{v_p}{v'}\right)^{k_2} \left(\frac{D_p}{D'}\right)^{k_3} \qquad (11)$$

$$g(\alpha) = (\sin\alpha)^{n_1} \left[1 + H_v(1 - \sin\alpha)\right]^{n_2} \qquad (12)$$

$$n_1 = s_1(H_v)^{q_1},$$

$$n_2 = s_2(H_v)^{q_2} \qquad (13)$$

where $E(\alpha)$ denotes the wall volume loss caused by particles of unit mass (mm^3/kg); E_{90} is the volume loss caused by particles impacting the wall vertically at 90°; $g(\alpha)$ is the impact-angle function. This formula can theoretically calculate the impact force of particles on the wall at any angle and any velocity. α denotes the angle at which a particle impacts the wall; K, k_1, k_2, k_3, n_1, and n_2 are empirical constants closely related to particle and wall properties; H_v is the wall Vickers hardness (GPa); v' and D' are the reference particle velocity (m/s) and particle size (mm); s and q are particle property parameters; and ρ_w is the wall material density (kg/m^3). In this study, the particles are sand, and the blade material is ultra-high molecular weight polyethylene (UHMWPE) [21]. According to the literature, the reference constants and exponents are $K = 65$, $k_1 = -0.12$, $k_2 = 2.3(H_v)^{0.038}$, $k_3 = 0.19$, $s_1 = 0.71$, $q_1 = 0.14$, $s_2 = 2.4$, $q_2 = -0.94$, $v' = 104$ m/s, and $D' = 0.326$ mm.

By analyzing the wear depth, the degree of wear caused by sand particles can be analyzed. The wear depth is the local damage volume at the minimum mesh size and can be calculated by the following formulas:

$$D'_w = \frac{1\,000 E_2(\alpha) m_p^i}{A_j} \qquad (14)$$

$$D_w^{\text{ave}} = \frac{\sum_j D'_w}{j} \qquad (15)$$

$$D_w^{\max} = \max(D'_w) \qquad (16)$$

where D_w denotes the wear depth (μm); $E_2(\alpha)$ denotes the erosion ratio (kg/kg) in the Oka formula; m_p denotes the mass of the wind-sand particle (kg); and D_w^{ave} and $D_w^{\max}$ denote the average wear depth and maximum wear depth, respectively.

The spectral synthesis method provides a method for generating pulsating-velocity components. It is a stochastic-turbulence-generation technique originally proposed by Kraichnan [22] and modified by Smirnov et al. [23]. In this method, the pulsating-velocity components are calculated by synthesizing a divergence-free velocity vector field from the sum of Fourier spectral waves. The main steps for generating a pulsating-wind-speed inlet by the spectral synthesis method include the following: first, prescribe an anisotropic velocity correlation tensor and find an orthogonal transformation tensor so that the velocity correlation tensor is diagonalized. As a result, both tensors become known functions of space. The coefficients in the new coordinate system represent the turbulent pulsating velocity:

$$r_{ij} = \tilde{u}_i \cdot \tilde{u}_j \qquad (17)$$

In the generated vortex field $\{\tilde{u}_i(x_j,t)\}_{i,j}$, find an orthogonal transformation—the transformation tensor $a_{i,j}$; it will be diagonalized as $r_{i,j}$,

$$a_{mi}a_{nj}r_{ij} = \delta_{mn}c_n^2 \qquad (18)$$

$$a_{ik}a_{kj} = \delta_{ij} \qquad (19)$$

After completing the above transformation, both a_{ij} and c_n become known spatial functions. At the new spatial coordinate positions, the coefficients $c_n = \{c_1, c_2, c_3\}$ of the fluctuating velocity (u', v', w') are generated; then, according to Eq. (20), the fluctuating velocity varying with time t is generated in the three-dimensional fluid domain. It is generated using the Kraichnan method. The inputs to this process are the correlation tensor and the length and time scales of the turbulence, and the result is a time-dependent flow field with a correlation function equal to the turbulent length/time scale of the original flow field. This flow field is nondivergent for homogeneous turbulence, and is highly nondivergent for inhomogeneous turbulence. Through construction, the correlation tensor of the flow field is diagonal,

$$v_i(x,t) = \sqrt{\frac{2}{N}}\sum_{n=1}^{N} p_i^n \cos\left(\tilde{k}_j^n \tilde{x}_j + \omega_n \tilde{t}\right) + q_i^n \sin\left(\tilde{k}_j^n \tilde{x}_j + \omega_n \tilde{t}\right) \qquad (20)$$

where l and t are the turbulence length and time scales, respectively; ω_n denotes the samples of the n wavenumber vectors and frequencies of the simulated turbulence spectrum. In Fluent, the default value of n is 100. Finally, the flow field generated in the previous step is orthogonally transformed using the turbulence spectrum $E(k)$ to obtain the new flow fields w_i, u_i,

$$E(k) = 16\left(\frac{2}{\pi}\right)^{1/2} k^4 \exp(-2k^2) \qquad (21)$$

$$w_i = c(i)v(i) \qquad (22)$$

$$u_i = a_{ik}w_k \qquad (23)$$

The spectral synthesis method provides flexibility in balancing the accuracy with which the turbulence spectrum is represented and the memory/time requirements. Because the flow field is calculated by analytical functions, its values are given at any point in space and time, rather than depending only on grid nodes and discrete time values as in numerical solutions. Therefore, as a subgrid-scale model for LES or RANS simulations, this method has certain potential when simulating turbulent fluctuating flows.

1.3 Geometric Model and Mesh Division

In this study, a three-dimensional computational model is used to perform numerical simulation of a vertical-axis wind turbine. The geometric model is shown in Fig. 1. The upper and lower boundaries are set as no-slip wall boundary conditions. The distance between the upper and lower boundaries is $10D$. The distance between the left boundary and the rotation center of the wind turbine is $5D$. The right boundary is set as the pressure-outlet condition, and the distance between the right boundary and the rotation center of the wind turbine is $10D$ [24], where D is the diameter of the rotating domain. The shaft and blade are set as no-slip conditions. Considering the influence of the rotating shaft on the internal flow field of the wind turbine, the entire computational domain is divided into three parts: the external domain, internal domain, and rotating domain. The wind-turbine blade rotates together with the rotating domain. The interface between the rotating domain and the external domain is set as an interface. By setting the angular velocity of the rotating domain, a sliding mesh can be constructed.

Fig. 1 Geometric model

To improve the solution speed, a structured mesh is selected for the computational-domain mesh division. To ensure computational accuracy for the complex flow near the wall, a boundary-layer mesh is set on the airfoil surface. The thickness of the first layer is determined by the following formula:

$$\Delta y = \mu y^+ / (\rho u_t) \qquad (24)$$

where μ is the dynamic viscosity of air; y^+ is the dimensionless value of the wall distance; ρ is the air density; and u_t is the wall friction velocity.

In this study, when the value of y^+ is 5, the best balance between computational cost and accuracy is obtained. The grid-independence verification will be introduced in detail in a later section. The final mesh selected for the computational domain, as well as an enlarged view of the mesh near the blade, is shown in Fig. 2.

Fig. 2 Computational domain and boundary layer mesh near blade

1.4 Simulated Operating Conditions and Particle Definition

With the continuous development of computational fluid dynamics, simulating and predicting particle motion in fluids has become increasingly important in research. At present, the discrete element method (DEM) has become a key method for simulating particle motion [25]. To realistically simulate particle behavior in complex fluid environments, the interaction between particles and the surrounding fluid must be considered. To achieve this objective, this study adopts a CFD-DEM coupled model. Fluent and EDEM are coupled, and two-way coupling between the fluid phase and the discrete phase is realized through a user-defined function (UDF). This coupling method can account for particle-fluid interaction forces. Through this CFD-DEM coupled model, more accurate simulation of particle motion in the fluid is achieved. This is crucial for studying particle behavior in two-phase flow.

Determining the time step is of crucial importance in CFD-DEM simulations. The particle time step is constrained by the Rayleigh time[^26] and is calculated using Eq. (25). To ensure the stability and accuracy of the numerical simulation, it is recommended that the time step be between 20% and 40% of the Rayleigh computational time step. For the fluid phase, its time step should be an integer multiple of the discrete-phase time step, with a range of 1–100 times. In this study, the discrete-phase time step Δt_R is 1×10^{-6} s, and the fluid-phase time step is 100 times this value, i.e., 1×10^{-4} s.

$$\Delta t_R = \frac{\pi R_i}{0.1631 v_i + 0.8766 \sqrt{\frac{2\rho_p(1+v_i)}{E_i}}} \qquad (25)$$

References [27-28] have shown that the wear caused by wind–sand particles impacting wind-turbine blades can be attributed to multiple factors. This study focuses on selecting three variables for numerical simulation. The simulation conditions considered in the numerical simulations are shown in Table 1. The main effects investigated are inlet pulsating wind turbulence intensity, wind-sand particle mass concentration, and sphericity.

In this study, particle shape is also a key factor affecting blade wear. The particle shape is reproduced by importing an external model for particle filling. The particle surface is represented as a point cloud with a specified spatial density. This is used to determine the interaction between particle shape and the blade. Common polyhedral particles such as tetrahedra, hexahedra, octahedra, dodecahedra, and spheres are studied to analyze the wear law of particle shape on the blade.

$$\varphi = \frac{S_s}{S_p} \qquad (26)$$

where S_s is the surface area of a sphere with the same volume as the particle, and S_p is the surface area of the given particle.

Table 1 Numerical simulation conditions

Tab. 1 Numerical simulation condition

Influencing factor	Inlet velocity turbulence intensity / %	Particle mass concentration / $(kg \cdot s^{-1})$	Particle sphericity
Inlet velocity turbulence intensity	0, 10, 30, 50	0.3	1
Particle mass concentration	0	0.1, 0.3, 0.5, 0.7	1
Particle sphericity	0	0.3	0.42, 0.6, 0.76, 0.81, 1

As shown in Table 2, D_e denotes the equivalent spherical diameter, and φ is the particle sphericity. Sphericity is a physical quantity used to measure the degree to which a particle shape approaches a sphere[^29]. The sphericity of a particle is defined as the ratio of the surface area of a sphere with the same volume as the given particle to the particle surface area.

Table 2 Particle filling diagram and its properties

Tab. 2 Particle fill diagram and its properties

Parameter	Regular tetrahedron	Regular hexahedron	Regular octahedron	Regular dodecahedron	Sphere
DEM model	[[image: yellow DEM model of regular tetrahedron]]	[[image: yellow DEM model of regular hexahedron]]	[[image: yellow DEM model of regular octahedron]]	[[image: yellow DEM model of regular dodecahedron]]	[[image: yellow spherical DEM model]]
φ	0.431	0.605	0.725	0.822	1

1.5 Grid independence and model validation

1.5.1 Grid independence validation

The results of numerical simulation should be affected by the grid size to the minimum possible extent. Therefore, it is necessary to conduct grid independence validation to ensure that the obtained numerical solution is not sensitive to the grid size. At present, the grid convergence index (GCI) method[^30] is mostly used for grid independence validation. A total of three sets of grids (G_1, G_2, G_3) were tested, with the number of grids decreasing successively. Grid G_1 has 2.37 million cells, while G_2 and G_3 are reduced to 1.58 million and 1.09 million, respectively. The average sizes of the three grid sets (G_1, G_2, G_3) are 1.65, 3.86, and 4.58 cm, respectively. The aerodynamic characteristic parameters of the vertical-axis wind turbine, namely the power coefficient C_P and thrust coefficient C_T, are selected as variables for grid independence validation. The blade power coefficient C_P is calculated as follows:

$$M = 0.5\rho v^2 ALC_{M\text{mean}} \qquad (27)$$

$$C_P = \frac{M\omega}{0.5\rho v^3 A_S} \qquad (28)$$

where ρ is the air density, v is the wind speed, A_S is the swept area, L is the characteristic length, and ω is the rotational angular velocity.

The blade thrust coefficient C_T is calculated as follows:

$$C_T = \frac{T_{\text{ave}}}{qA_S} \qquad (29)$$

where T_{ave} is the average thrust, which can be calculated from the thrust output of the final revolution in Fluent; q is the dynamic pressure.

Table 3 presents the calculation results obtained using the three grid sets. Φ_1, Φ_2, and Φ_3 represent the power coefficients obtained from the numerical simulations of the three grid sets, respectively.

coefficient C_P and thrust coefficient C_T, and G_{GCI}^{21} denotes the relative error between the C_P and C_T obtained from grid G_2 relative to grid G_1. It can be seen that, even for the coarsest grid G_3, the numerical relative error is quite small. For the medium grid G_2, the maximum relative error of the power coefficient is 0.033%. Similarly, the maximum relative error of the thrust coefficient is 0.029%. From G_2 to G_1, the GCI is very low. Therefore, selecting the medium grid with 1.58 million cells for the simulation can reduce the computational cost without greatly affecting the solution accuracy.

Table 3 Grid independence verification

Tab. 3 Grid independence verification

Parameter	C_P	C_T
Φ_1	0.328 6	0.579 6
Φ_2	0.332 1	0.585 4
Φ_3	0.335 9	0.598 7
G_{GCI}^{21}	0.005 81%	0.001 85%
G_{GCI}^{32}	0.033 12%	0.032 45%

Fig. 3 Turbulence model validation

Figure 1: Fig. 3 Turbulence model validation

1.5.2 Turbulence model validation

First, the accuracy of the large-eddy simulation (LES) turbulence model used in the simulation is verified. Using the same geometry and boundary conditions as Zhang et al. [31], after convergence the average torque coefficient $C_{M\text{mean}}$, wind-turbine torque M, and wind-energy utilization coefficient C_P are output; C_P can be calculated according to the above formula. Finally, the wind-energy utilization coefficients under different tip-speed ratios are obtained and validated, as shown in Fig. 3. Comparing the wind-energy utilization coefficient with the experimental data and the SST k-ω turbulence model, it can be seen that the results obtained by the LES model are higher than the experimental data, but more accurate than those of the SST k-ω model. This phenomenon can be explained according to the study of Yan et al. [32]: after flow separation, LES produces more realistic 3D vortex diffusion, thereby predicting the aerodynamic coefficient more accurately. However, the deficiency is that LES cannot capture the influence of the tip vortex, which has been regarded by some researchers as the main reason for overprediction of VAWT power.

Fig. 3 Turbulence model validation

1.5.3 Wear model validation

According to the experimental data of Özen et al. [33], the accuracy of the CFD-DEM Oka erosion model is verified. A three-dimensional rectangular flow field is established, and a stationary three-dimensional single-wing airfoil is placed at the bottom. The airfoil wall material is set as glass-fiber-reinforced epoxy resin (GF/EP), and the wear rate under different impact angles is simulated for impact velocities of 70 and 110 m/s in the experiment. The CFD–DEM calculation results are compared with the experimental data, as shown in Fig. 4. Comparing the erosion rates predicted by the CFD–DEM Oka erosion model with the experimental data, it can be seen that when the impact velocity is 70 m/s, there is a certain error between the simulated values and the experimental values, but the overall trend of the predicted variation is consistent with the experimental values; when the impact velocity is 110 m/s, the simulated values are relatively close to the experimental values, and the trend of variation is also consistent, with the overall error remaining within 5%. There are many factors causing the differences between the simulated and experimental values. Numerical simulation, as a predictive tool compared with experiments, is bound to have certain errors. As long as the overall variation trend is the same, the error should be allowed within a certain range. This further verifies the accuracy of the prediction results of the CFD–DEM Oka model.

Fig. 4 Oka wear model verification

Fig. 4 Oka wear model verification

Figure 2: Fig. 4 Oka wear model verification

Fig. 5 Pulsation velocity changes under different turbulence intensities

Figure 3: Fig. 5 Pulsation velocity changes under different turbulence intensities

2 Results and discussion

2.1 Influence of inlet turbulence intensity

In this study, considering that the incoming wind speed continuously varies under the actual operating conditions of a wind turbine, a fluctuating-velocity inlet is adopted in the simulation process so as to better approximate the actual operating conditions experienced by a wind turbine. According to the synthetic-eddy method described by Keating et al. [34], the mean inlet velocity is first defined, and then the actual turbulent fluctuations are superimposed on this mean velocity. The key parameter characterizing the intensity of these fluctuations is called the turbulence intensity (T_i). To understand the influence of T_i on the erosion model of the turbine blades, this study simulates four different turbulence intensities, namely T_i = 0%, 10%, 30%, and 50%. The mean inlet velocity is held constant at 12 m/s, the particle mass flow rate is set to 0.1 kg/s, and the particle shape is spherical, with sphericity of 1 and diameter of 100 μm. Under the condition T_i = 0%, the inlet velocity remains nonfluctuating and is always maintained at 12 m/s. In contrast, when T_i = 10%, 30%, and 50%, the monitored inlet velocity exhibits temporal fluctuations, as shown in Fig. 5, from which it can be clearly seen

It can be seen that, as the turbulence intensity at the inlet increases, the change in inlet velocity over time also becomes more pronounced. When the turbulence intensity reaches the level of 50%, the maximum inlet velocity is about 25 m/s, while the minimum inlet velocity is only about 6 m/s.

Fig. 5 Pulsation velocity changes under different turbulence intensities

Figure 6 presents comparison cloud images of the erosion depth of the same blade at the same simulation time under different turbulence intensities. Clearly, the leading-edge region of the blade experiences the most pronounced erosion during the operation of a vertical-axis wind turbine in a wind-sand environment. Moreover, at the same instant, the greater the turbulence intensity, the more evident the erosion depth. This phenomenon is mainly attributable to the velocity parameter, which has a significant influence on the Oka erosion model. The erosion depth predicted by the Oka erosion model is proportional to a power of velocity. Therefore, the greater the inlet turbulence intensity, the wider the range of pulsation-velocity variation; the maximum pulsation velocity approaches about 30 m/s, and the erosion caused when incoming wind-sand particles impact the blade becomes more pronounced.

Fig. 6 Blade surface erosion cloud images under different turbulence intensities of the same blade

Figure 4: Fig. 6 Blade surface erosion cloud images under different turbulence intensities of the same blade

Fig. 7 Average wear depth D_w^ave of blade under different turbulence intensities

Figure 5: Fig. 7 Average wear depth D_w^ave of blade under different turbulence intensities

Fig. 6 Blade surface erosion cloud images under different turbulence intensities of the same blade

Figure 7 shows the average blade-surface erosion depth calculated after completion of the simulation under different turbulence intensities. It can be seen that the average erosion depth of the blade exhibits an obvious correlation with turbulence intensity. An increase in turbulence intensity causes the average erosion depth of the blade to increase gradually. This phenomenon can be understood through the process in which wind-sand particles strike the blade: an increase in turbulence intensity generates more extensive velocity fluctuations, thereby increasing the velocity of particles entering the sand stream and the energy they carry, and thus producing a greater impact force during collision. It is worth noting that these high-speed sand particles often deflect when striking the blade, thereby increasing the possibility of secondary collisions. This, in turn, further intensifies overall erosion and increases the average erosion depth of the blade, resulting in an increase in the average erosion depth on the blade surface. The research results of Mathavan et al. [35] can explain this phenomenon. The variation in turbulence intensity is the reason for the different ranges of inlet pulsation velocity. An increase in turbulence intensity leads to more drastic changes in pulsation velocity, which in turn causes changes in the impact angle of sand particles. Changes in the impact angle further affect changes in the particle impact location, and the erosion depth also changes with the above-mentioned impact-velocity variation.

Fig. 7 Average wear depth D_w^{ave} of blade under different turbulence intensities

2.2 Effect of particle mass concentration

The mass concentration of wind-sand particles is one of the key parameters affecting erosion. This section mainly simulates the influence of incoming wind-sand particles with different mass concentrations on the surface erosion of vertical-axis wind turbine blades. With the incoming wind speed kept stable at 12 m/s, the particle shape is spherical, the sphericity is 1, the diameter is 1 mm, and the mass concentrations are 0.1, 0.3, 0.5, and 0.7 kg/s, respectively. After the simulation is completed, the erosion data are output, and the changes in the average erosion depth and maximum erosion depth on the blade surface with the mass concentration of wind-sand particles are obtained, as shown in Fig. 8. It can be seen from the figure that the mass concentration of incoming wind-sand particles has a significant influence on both the maximum and average erosion depths on the blade surface. As the particle concentration increases, both the maximum and average erosion depths increase significantly. The erosion depth and particle mass concentration show an almost linear relationship. This is because, when the particle diameter is fixed, a multiple increase in particle concentration causes the number of particles impacting the blade to increase by nearly the same multiple; therefore, the concentration and erosion amount vary almost linearly.

[Figure 8 plot]

Figure 8 Variation of the average and maximum erosion depths of the blade with mass concentration

Fig. 8 The average and max erosion depth of the blade surface changes with the particle mass concentration

2.3 Effect of particle sphericity

With other parameters kept constant, regular tetrahedral, regular hexahedral, regular octahedral, regular dodecahedral, and spherical particles were simulated separately. The equivalent diameter of the particles was 1 mm. Figure 9 shows the variation relationships, obtained after the simulations, of the average and maximum erosion depths of the blade surface with particle sphericity.

[Figure 9 plot]

Figure 9 Variation of the average and maximum erosion depths of the blade with particle sphericity

Fig. 9 The average erosion depth $D_{\mathrm{w}}^{\mathrm{ave}}$ and max erosion depth $D_{\mathrm{w}}^{\max}$ of blade surface changes particle sphericity

It can be seen that there is an approximately inverse proportional relationship between particle sphericity and the maximum erosion depth on the blade surface. As particle sphericity increases, the maximum erosion depth decreases significantly. The reason for this phenomenon can be explained as follows: under the same incoming-flow wind speed, although the particle equivalent diameter is the same, different particle shapes lead to changes in the particle motion mode. Particles with higher sphericity experience less resistance when moving in the flow field, and therefore have fewer opportunities to collide with the blade surface, resulting in smaller average and maximum erosion depths than particles with lower sphericity. In addition, during the process in which wind-sand particles strike the blade surface and cause erosion, the blade is mainly subjected to the tangential impact and normal pressing action of the wind-sand particles. A decrease in particle sphericity intensifies the normal pressing action of the particle surface during collision, leading to an increase in erosion depth. Compared with the maximum value of erosion depth, when the sphericity is below 0.7, the variation pattern of the average erosion depth shows an almost consistent behavior; however, when the sphericity exceeds 0.7, the erosion depth no longer changes noticeably with sphericity. This can be explained as follows: when the sphericity exceeds 0.7, the shape of the polyhedron can be approximated as a spherical particle, and the erosion characteristics of the blade surface can likewise be approximated as those of spherical particles. Therefore, the change in average erosion depth corresponding to sphericity shows only a negligible variation.

Figure 10 depicts the variation relationship between the blade-surface erosion rate and particle sphericity. Through data fitting, an approximate functional curve between these two variables is established. The erosion rate of the blade surface is proportional to the -1.32 power of particle sphericity, and this relationship can be used to approximately predict the erosion rate of blade surfaces caused by wind-sand particles with different sphericities.

[Figure 10 plot]

Figure 10 Blade surface erosion rate $E(\alpha)$ under different sphericities

Fig. 10 Blade surface erosion rate $E(\alpha)$ under different sphericity

3 Conclusions

Based on CFD-DEM two-way coupling, the erosion characteristics of a vertical-axis wind turbine in a dust-laden environment were studied. The Oka erosion model was selected to simulate the interaction between wind-sand particles and the blades of the vertical-axis wind turbine. The main parameters studied included the turbulence intensity of the inlet fluctuating wind speed, the mass concentration of sand-dust particles, and the influence laws of particle sphericity on blade erosion parameters. The following conclusions were obtained.

1) Compared with the mean inlet wind speed, considering the inlet wind-speed fluctuation increases the average erosion depth of the blade surface. As the turbulence intensity of the inlet fluctuating wind speed increases, the average erosion depth increases significantly, and the two variables are almost linearly positively correlated. The erosion depth at the leading edge of the blade increases with increasing turbulence intensity. From the erosion cloud map, it can be observed that the main locations of erosion are concentrated in the leading-edge region of the blade; increasing the turbulence intensity of the fluctuating wind speed does not change the region where erosion occurs.

2) As the mass concentration of dust particles increases, both the maximum erosion depth and the average erosion depth on the blade surface increase

approximately linearly with the increase in the mass concentration of incoming dust particles.

3) As particle sphericity increases, the maximum erosion depth decreases significantly, showing an approximately linear relationship; the average erosion depth also decreases.

significantly smaller. What differs is that, when the particle sphericity is greater than 0.7, the average erosion depth no longer changes markedly with particle sphericity. By fitting the approximate functional relationship between erosion rate and sphericity, the erosion rate on the blade surface is proportional to the -1.32 power of the particle sphericity.

4) By analyzing the erosion data under the influence of different parameters, it can be concluded that the mass concentration of sand particles has the most important effect on the erosion of wind-turbine blades, because it directly determines the impact energy and frequency of wind-blown sand on the blade surface. A higher mass concentration of sand particles means that there are more sand particles per unit volume, which not only increases the probability of contact between sand particles and the blade, but also increases the number of sand-particle impacts received by the blade surface within a given time.

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