Critical Stokes Number for Gas-Solid Flow Erosion of Wind Turbine Airfoil

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Abstract: Wind turbine blades are inevitable to be eroded in wind-sand environment, so it is crucial to identify the flow conditions under which the erosion happens. Here, the effect of the sand diameter on wind turbine airfoil is first investigated. When the sand diameter is less than 3 μm, the sands will bypass the airfoil and no erosion occurs. When the sand diameter is larger than 4 μm, the sand grains collide with the airfoil and the erosion happens. Thus, there must be a critical sand diameter between 3 μm and 4 μm, at which the erosion is initiated on the airfoil surface. To find out this critical value, a particle Stokes number is introduced here. According to the range of the critical sand diameter mentioned above, the critical value of particle Stokes number is reasonably assumed to be between 0.007 8 and 0.014. The assumption is subsequently validated by other four factors influecing the erosion, i. e. , the angle of attack, relative thickness of the airfoil, different series airfoil, and inflow velocity. Therefore, the critical range of Stokes number has been confirmed.

Key words: wind turbine airfoil erosion; critical Stokes number; gas-solid two-phase flow

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0 Introduction

Wind power, currently at the stage of scale-up development, is regarded as an important alternative power source. The wind resource in northwest China is abundant. Although it provides eligible renewable energy, the wind blows dust and sand, raising huge clouds of dust known as dust storm, one of wind-blown sand hazards. Wind turbine blades, running in such a harsh environment, suffer long-term erosion and the performance of wind turbine will degrade. The erosion eventually worsens the aerodynamic characteristics of wind turbine and reduces its annual power generation. Li et al. [1] pointed out that for the rough airfoil, the lift coefficient could decrease to about 40% and the drag coefficient could increase by ten times compared with that of the smooth one. Sareen et al. [2-5] investigated the effect of leading-edge erosion of wind turbine blade, and found that the blade leading-edge erosion could be extremely detrimental to wind turbine. The loss of annual energy production due to the impact of erosion could be as high as almost 25% for the modern wind turbines. Dong[6] studies the sand erosion behaviours of wind turbine blade materials by experimental method.

The critical Stokes number range of wind turbine airfoil erosion is discussed here via the numerical simulation based on particle transport model. The influences of other factors on the critical range are also analyzed.

1 Numerical Simulation

1.1 Computational domain

The length and the width of three-dimension-

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al (3-D) calculation domain are 32.5 times and 25 times larger than the airfoil chord length, respectively, as shown in Fig. 1. And the blade spanwise width is 70 mm. Structured grid scheme is adopted to simulate the gas-solid two-phase flow. After verifying the validity of different scales of the grid structures, it is confirmed that the scheme, where the grid height of the first layer around the airfoil is selected for 0.01 mm, is the most suitable one for the calculation, as shown in Fig. 2.

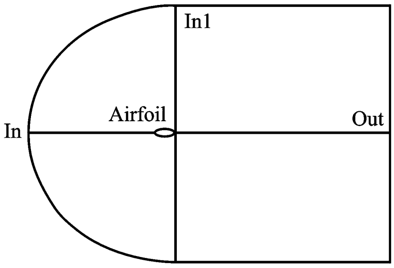


Fig. 1 Schematic representation of computational domain

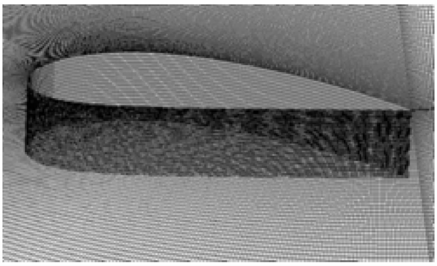


Fig. 2 3-D grid around airfoil

1.2 Computational models

Since the solid phase is dilute and its Mach number is lower than 0.3, the following assumptions are made: (1) The gas phase (air) is incompressible fluid and the solid phase (sand) the discrete phase. (2) The particle is uniform-sized spherical without phase transition. (3) The particle collision and the influence of particle rotation are ignored. The governing equations of the fluid phase are continuity equation and incompressible Reynolds-averaged Navier-Stokes equations (RANS), which are discretized by the method of finite volume. The turbulence mode is the standard k-ε model. And the semi-implicit method for pressure linked equations (SIMPLE) algorithm is used to solve the pressure-velocity coupling[7-8]. The parameters of the fluid phase are 1.225 kg • m^{-3} for the air density and 1.79×10^{-5} kg • m^{-1} • s^{-1} for the air dynamic viscosity coefficient, respectively. The particle transport model is adopted to predict the solid phase movement.

1.3 Boundary conditions

The velocity boundary condition is defined at inlet with a turbulence intensity of 10%. The pressure boundary condition is defined at outlet at one standard atmospheric pressure. According to the analysis of sand characteristics parameters under sandstorm environment in Refs. [9-11], in this paper, the dust concentration is fixed to 5 000 μg • m^{-3} to study the erosion on wind turbine airfoil. Solid phase is injected into the flow field at the inlet, where the particles are uniformly distributed, and the injection velocity of solid phase is equal to that of gas phase. The sand density is 2 200 kg • m^{-3}. There is no-slip velocity between solid phase and gas phase. Particle is completely escaped at outlet. The drag interaction between the two phases is described by the Schiller-Naumann model . The airfoil surface is regarded as a smooth wall. No-slip assumption is taken as the boundary condition, and the impact between the particle and airfoil is supposed as perfectly elastic collision. The erosion model established by Grant and Tabakoff[12] is used to study the erosion characteristics, and the maximum erosion angle is set as 90° because the epoxy gel-coat of blade is brittle.

2 Results and Discussions

2.1 Proposal of critical Stokes number

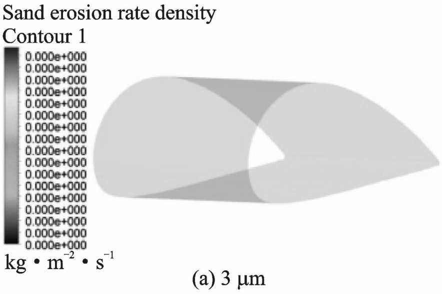
The Stokes number of particle is the most important dimensionless parameter in a gas-solid two-phase flow, which is derived by Shvab and Evseev[13] to evaluate particle movement following the airflow. The Stokes number can be defined as the ratio of particle response time to the system response time, expressed by the equation

$$St=\frac{\tau_d}{t_s}$$

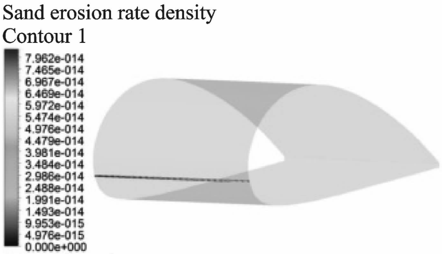
where $\tau_d=\dfrac{\rho_d d^2}{18\mu}$. t_s is the time related to the characteristic length and the characteristic velocity v_s of the system through the formula $t_s = L_s / v_s$.

For airfoil, the characteristic length is the chord length and the characteristic velocity is the inflow velocity. When $St \ll 1.0$, the particles will closely follow the gas phase flow. When $St > 1.0$, the particles will move independently as the gas phase flows[14].

In this section, an airfoil of a wind turbine blade for field experiment[15] of Lanzhou University of Technology is chosen as research subject. The chord length of airfoil NACA4418 is 0.283 m. The relative inflow velocity is 36.36 m • s^{-1} and the angle of attack of the airfoil is 9.47°. By simulating the influence of sand diameter on the NACA 4418 airfoil, it is found that when the sand diameter is less than 3 μm, the sands bypass the airfoil and no erosion occurs, as shown in Fig. 3(a). However, when the sand diameter is larger than 4 μm, a few sand particles collide with the airfoil and cause erosion, as shown in Fig. 3(b). Therefore, when the velocity is 36.36 m • s^{-1}, the erosion occurs with the diameter between 3 μm and 4 μm, which corresponds to the range of the particle Stokes number from 0.007 8 to 0.014. Typically, it can be assumed that there may exist a Stokes number critical range between 0.007 8 and 0.014 which can be used to forecast whether the erosion happens on wind turbine airfoil.

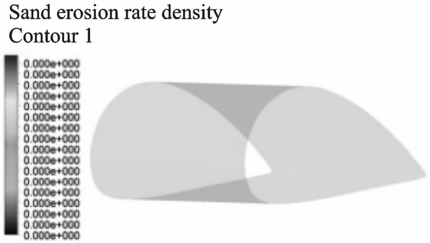


(a) 3 μm

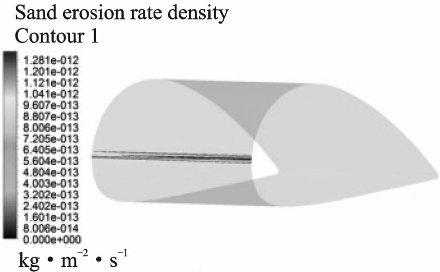


(b) 4 μm

Fig. 3 Erosion on airfoil with different sand diameters



(a) 3 μm



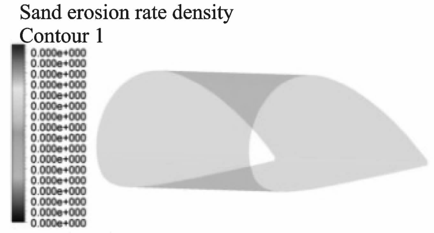
(b) 4 μm

Fig. 4 Erosion on airfoil with attack angle of 0°

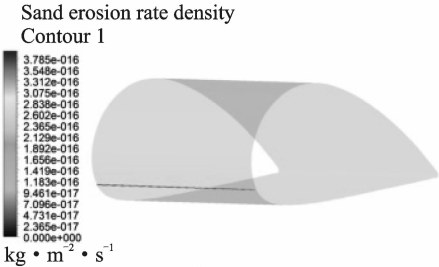
2.2 Validation

To validate the correctness of the Stokes number critical range, we discuss the effects of the angle of attack, relative thickness of airfoil, different series airfoil, and inflow velocity on airfoils erosion respectively.

Firstly, the effect of airfoil attack angle on the Stokes number critical range is investigated with three different attack angles of 0°, 5° and 15° for the NACA 4418 airfoil at the inflow velocity of 36.36 m • s^{-1}. The results are illustrated in Figs. 4, 5, 6. It can be seen that for all the three different angles of attack no erosion takes place when the sand diameter is 3 μm , as shown in Figs. 4(a), 5(a), 6(a). Nevertheless, when the

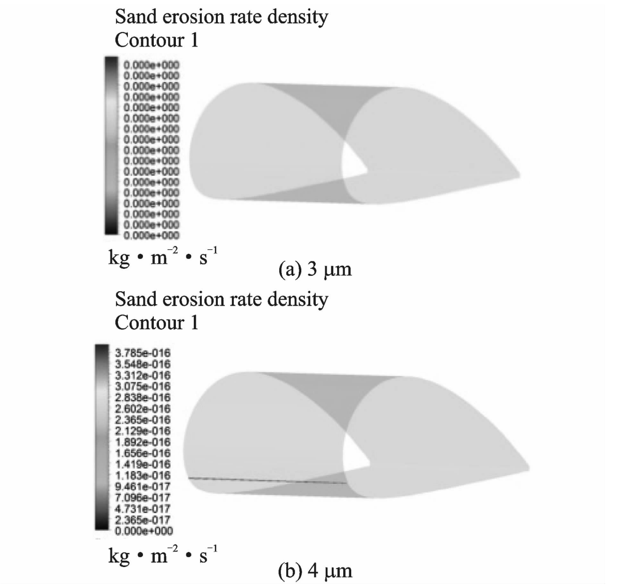


(a) 3 μm



(b) 4 μm

Fig. 5 Erosion on airfoil with attack angle of 5°



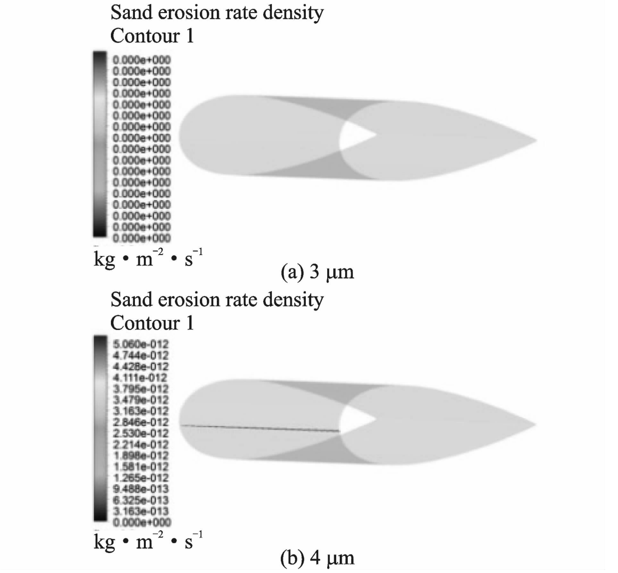
(a) 3 μm

(b) 4 μm

Fig. 6 Erosion on airfoil with attack angle of 15°

sand diameter is 4 μm, the erosion happens in all the three cases, as shown in Figs. 4(b), 5(b), 6(b). Therefore, it can be concluded that the angle of attack hardly influences the critical range of Stokes number.

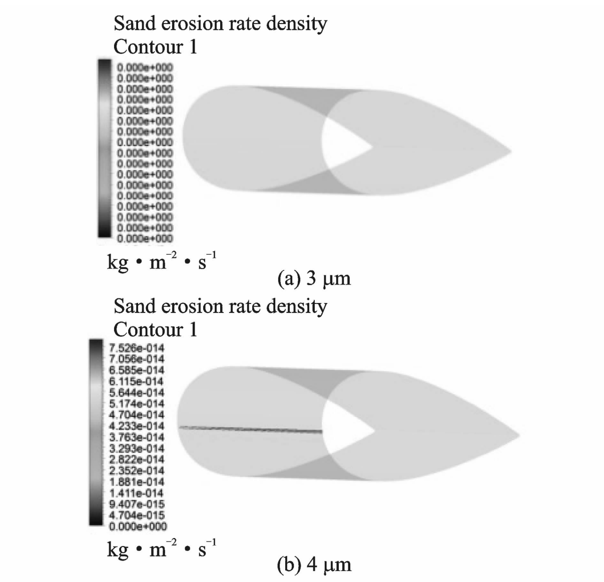
Secondly, the critical ranges of Stokes number are calculated for three symmetrical airfoils, i. e. , NACA 0012, NACA 0018 and NACA 0024, to verify that the critical range of Stokes number is irrelevant to relative airfoil thickness. It is revealed that sands do not erode the airfoil at all for all the three different relative thickness when the sand diameter is 3 μm, as shown in Figs. 7(a), 8(a), 9(a). When the sand diameter is 4 μm, the airfoil erosion occurs on all the three cases as shown in Figs. 7(b), 8(b), 9(b). Therefore, the critical range of Stokes number is not affected by relative airfoil thickness.



(a) 3 μm

(b) 4 μm

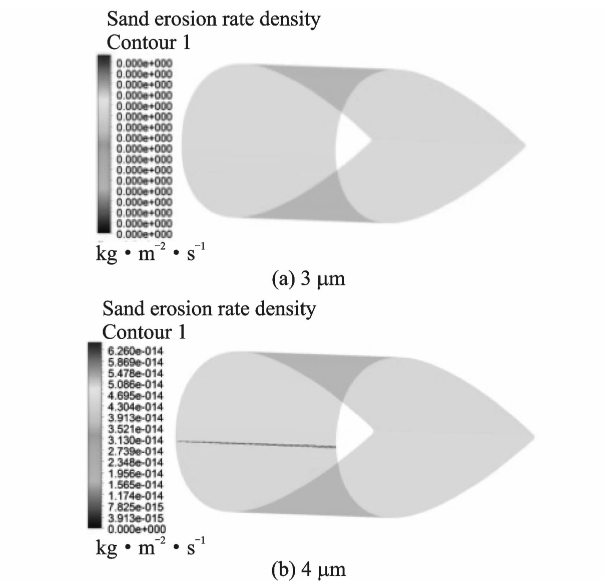
Fig. 7 Erosion on NACA 0012 airfoil



(a) 3 μm

(b) 4 μm

Fig. 8 Erosion on NACA 0018 airfoil

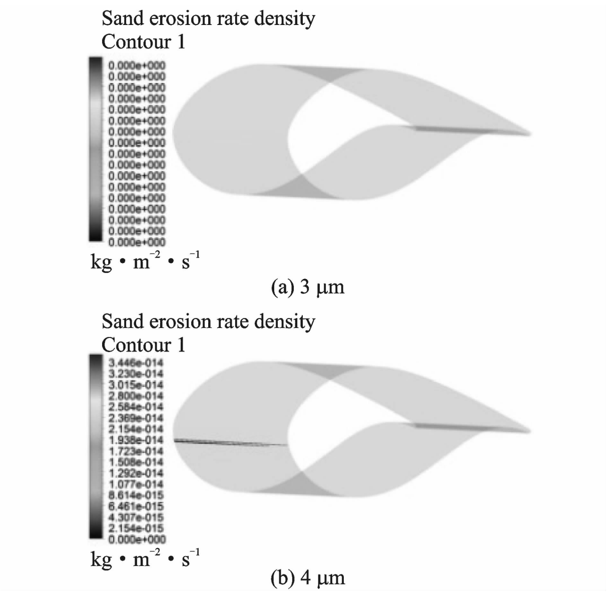


(a) 3 μm

(b) 4 μm

Fig. 9 Erosion on NACA 0024 airfoil

In order to find out whether the critical range of Stokes number is also appropriate to other series airfoil, the airfoil DU 91-W2-250, which can represent the DU series airfoils, was selected in the simulation. It is demonstrated that both the NACA series airfoil and other airfoil series are appropriate for the critical range of Stocks number. It is obvious that there is no erosion when the sand diameter is 3 μm, as shown in Fig. 10(a). Whereas with the sand diameter of 4 μm, the erosion occurs on the airfoil, as shown in Fig. 10(b).



(a) 3 μm

(b) 4 μm

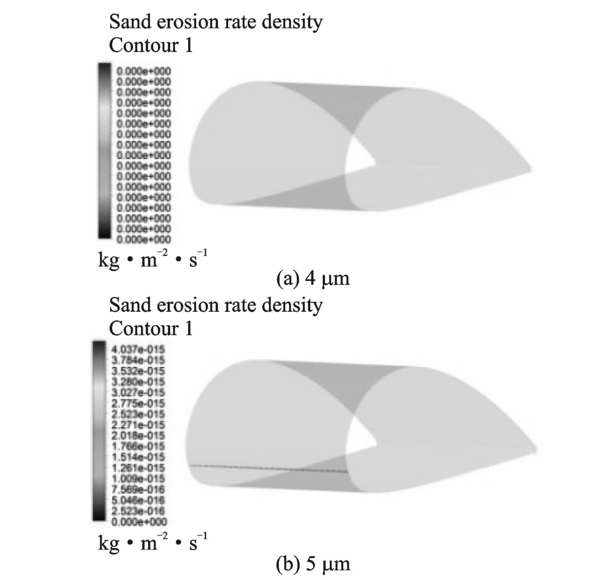
Fig. 10　Erosion on DU 91-W2-250 airfoil

Therefore, we confirm that the critical range of Stokes number is irrelevant to airfoil series.

Finally, the inflow velocity is introduced to examine the airfoil erosion. It is found that when the inflow velocity is 18 m/s and the sand diameter 4 μm, the Stokes number is 0.006 95 without any erosion on the airfoil. While the sand diameter is 5 μm, the Stokes number is 0.010 86, and the erosion occurs on the airfoil. When the inflow velocity is 50 m/s and the sand diameter 2 μm, the Stokes number is 0.004 83 which is less than 0.007 8, and there is no erosion on the airfoil; When the sand diameter is 3 μm, the Stokes number is 0.010 86, and the erosion occurs on the airfoil. Conclusions can be drawn that the erosion is not going to happen when the Stokes number is less than 0.007 8, as shown in Figs. 11(a), 12(a). But the airfoil is eroded when the Stokes number is larger than 0.010 86, as shown in Figs. 11(b), 12(b). Thus, the critical range of Stokes number can be narrowed to the one between 0.007 8 and 0.010 86.

3　Conclusions

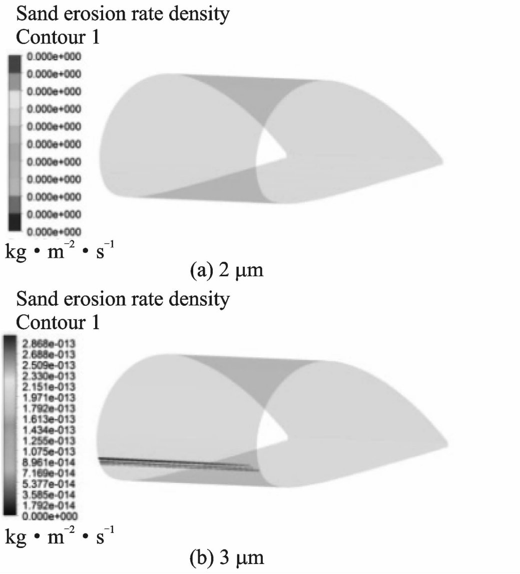
The critical range of particle Stokes number is proposed by analyzing the effect of sand diameter on the wind turbine airfoil gas-solid two-phase flow erosion to determine the specific flow conditions under which the erosion occurs. The critical range of Stokes number is confirmed to be between 0.007 8 and 0.010 86 by addressing the effects of other factors, such as angle of attack, relative thickness of airfoil, different airfoil series, and inflow velocity.



(a) 4 μm

(b) 5 μm

Fig. 11　Erosion at velocity of 18 m • s^{-1}



(a) 2 μm

(b) 3 μm

Fig. 12　Erosion at velocity of 50 m • s^{-1}

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