Study on aerodynamic performance of mine air duct horizontal axis wind turbine based on breeze power generation

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Abstract
The development of wireless sensor network based on breeze power generation is of great significance to promote the development of the intelligent mine. According to the underground environment of coalmine, a small horizontal axis wind turbine with mine air duct was designed. The aerodynamic performance of the wind turbine was analyzed by constructing the three-dimensional solid model of the wind turbine. The results show that under the condition of underground low wind speed. Outer basin: the air flow entering the air duct is accelerated and rectified, and the speed increases near the impeller. The pressure value at the front end of the blade is the largest and the pressure value at the rear end of the blade is the smallest. A certain range of negative pressure zone is formed at the rear end of the impeller, which is conducive to the operation of the wind turbine. After passing through the impeller, the speed of the air flow decreases and is the lowest near the impeller rotating shaft. Inner basin: the air flow speed gradually increases along the radial direction of the impeller center. The pressure at the front end of the blade is greater than the atmospheric pressure, which is conducive to facilitating the operation of the wind turbine. When the wind speed reaches the rated wind speed of the wind turbine, the power, torque, and output power of the wind turbine increase, which can provide effective power generation. Compared with other airfoils, NACA5505 airfoil has higher lift drag ratio and thrust coefficient. Compared with the wind turbine without air duct, the wind turbine with air duct has higher wind energy conversion and output power under the condition of low Reynolds number, which verifies the feasibility of the wind turbine with air duct.

Keywords
air duct, horizontal axis wind turbine, intelligent coal mine, micro-wind power generation, pneumatic performance
1 | INTRODUCTION

With the rapid development of wireless communication and sensor technology, wireless sensor networks are widely used in the field of coal mines to meet the needs of intelligent coal mines.\textsuperscript{1-4} However, unlike other areas, the mine working face is an environment that develops dynamically with the mining progress, and the wireless nodes can only run on batteries. Once the nodes are arranged, due to the poor environment, the sensor cannot replace the battery, which leads to the short life of wireless network and reduces the practicability of the wireless sensor network in the coal mine. Therefore, it is an important link to ensure the modern production of coal mine to realize the self-supply of wireless sensors in the coal mine.

Because of its simple structure, easy maintenance, and low starting wind speed, small wind turbine has become an indispensable form of energy supplement in low wind speed areas.\textsuperscript{5-7} If small wind turbine can be used to convert the wind energy in the roadway into stable electric energy to provide energy for the sensor system, it is of great significance to the development of mining wireless sensor networks. And the research on aerodynamic performance is an essential link in the design of small wind turbines.\textsuperscript{8-10} Hassanpour et al.\textsuperscript{11} optimized the aerodynamic performance of vertical axis wind turbines (VAWTs) and determined the best wind angle of vertical and horizontal distance of wind turbines. Li et al.\textsuperscript{12} believe that in an urban environment, dual VAWTs are expected to demonstrate more advantage than horizontal axis wind turbine. Twelve double VAWT wind tunnel tests and six isolated VAWT wind tunnel tests were carried out to study the effects of rotor robustness and other characteristics on the power output of reverse rotating double VAWT under the condition of low turbulence intensity and different rotor center spacing. The results show that in the urban environment, compared with the isolated VAWT under low wind speed, the dual VAWT configuration has less effect on the power output of VAWT, but this effect improves slightly with the increase of rotor robustness. Saulescu et al.\textsuperscript{13} presented a new concept of wind power system. The wind power system has a reverse rotating wind rotor, which can integrate traditional or reverse rotating generators through the same differential planetary speed increaser. The purpose is to compare and analyze the energy performance of reverse rotating wind turbine and conventional generator. A general analysis model of angular velocity and torque has been developed, which can be customized for two system configurations. Compared with the traditional generator, the wind power system with reverse rotating generator has higher efficiency and higher magnification. In addition, the analyzed wind power system with reverse rotating generator shows better energy performance when the output power and input speed are relatively low, while the wind turbine with traditional generator is proved to be more effective in the high range of the above parameters. Verma et al.\textsuperscript{14} studied the influence of airfoil aerodynamic characteristics Reynolds number on small horizontal axis wind turbine blades and found that appropriate Reynolds number setting has an important impact on blade tip speed ratio and power coefficient. Barnes et al.\textsuperscript{15} systematically described the challenges faced by the development of VAWTs. Lee et al.\textsuperscript{16} designed the optimal shape of the blade using an artificial neural network and genetic algorithm and analyzed the aerodynamic performance of the wind turbine blade through numerical simulation. The research results reduce the energy cost of the wind turbine blade and improve the performance of horizontal axis wind turbine. Altaae et al.\textsuperscript{17} optimized the performance of 20 kW horizontal axis wind turbine and improved the local annual power generation based on the local actual wind speed in New South Wales, Australia. Xuan et al.\textsuperscript{18} designed a special wind energy collection system and calculated the maximum efficiency parameters of the wind turbine. Under the load of 15Ω and the wind speed of 0~18 m/s, the maximum power generated by the wind turbine is 60 MW.

In addition, in the research of wind turbine with wind air duct, FloDesign,\textsuperscript{19} located at the American Institute of Aeronautical Engineering, has developed a wind turbine structure better than the traditional wind turbine. The system arranges sunshades around the wind turbine blades to guide the air to increase the movement through the impeller and accelerate the wind flow and improve the power of wind turbine. Ohya et al.\textsuperscript{20,21} studied and manufactured the light wind turbine with the best operation effect in low wind speed areas. The experiment of the research project with 500 W wind turbine shows that the efficiency of the power generation device can reach 5 times that of general wind turbine. In the same period, Tsinghua University and ABE\textsuperscript{22} cooperated to build a wind turbine with rated capacity of 13 kW. Modern energy demonstration base was built in Changping campus of Tsinghua University. Under the same wind environment, the wind speed and production power in the impeller area can be increased by at least 1.5 times. After more than one year of data statistical analysis, it is found that this wind pool wind turbine has significant wind pool capacity, which improves the utilization efficiency of wind resources. Chen et al.\textsuperscript{23} have made some innovations in the wind turbine design system. In order to improve the utilization rate of wind energy, a blade was set at the inlet and outlet ends of the wind turbine, a large four blade was installed at the inlet end, and a small five blade was installed at the outlet. In this way, due to the blocking effect of two impellers, wind speed can be greatly utilized.
Werle et al.\textsuperscript{24} conclude that ducted turbines are theoretically capable of extracting significantly more power than a bare wind/water turbine. Li\textsuperscript{25} presented a new definition of power coefficient of tidal current turbine systems to evaluate the reference power of ducted and unducted turbines together based on the same criterion. Dabir\textsuperscript{26} deduced a theoretical framework beyond the Bates limit based on the Bates theoretical limit and assumptions, which can guide the design, characterization, and optimization of such unsteady hydrodynamic energy conversion devices. For the optimized actuator disk motion, the minimum power coefficient is the limit value of Bates, and the time average power coefficient is improved. Klaptocz et al.\textsuperscript{27} carried out a ducted vertical axis tidal current turbine numerical and experimental investigation. The experimental results are used for validation and calibration of two numerical models: a 2D RANS model and a 3D Free Vortex model. Both models show good agreement with experimental results. The advantages and limitations of the numerical approaches are discussed. To facilitate the validation of numerical model, the laboratory experiment has been carried out by using three different types of NACA aerofoil connecting arm and circle section connecting arm. A further study has been performed, and a conclusion is drawn that the aerofoil and thickness of connecting arm are the most important factors on the power conversion coefficient of the vertical axis tidal current turbine. An optimization study\textsuperscript{28} was conducted to find the duct shape that maximizes the output power of a vertical axis turbine. The optimized ducts results show a higher power coefficient for the turbine relative to the results of experimentally tested ducts. It is also shown that there is an upper limit to the amount of increase in power coefficient due to ducting.

However, most of the above studies are applicable to medium-sized and large-scale wind turbines, not to small wind turbine with air duct. At present, there are few studies on small wind turbine with air duct suitable for underground narrow space. Therefore, aiming at the special environment such as low underground wind speed and small space, this paper designs a horizontal axis wind power generation device with air duct, the windward device needs to be designed for underground wind power generation. By constructing the three-dimensional solid model of the wind turbine, the performance of the wind turbine under different working conditions is analyzed by using ANSYS numerical simulation software. At the same time, in order to verify the rationality of airfoil selection in the design stage of the wind turbine, the performance of wind turbine with different airfoils is analyzed. By comparing the aerodynamic performance of wind turbines with air duct and without peripheral structure, the superiority of the designed wind turbine with horizontal axis is verified.

## 2 DESIGN OF AIR DUCT AND WIND TURBINE

Underground wind energy widely exists in various roadways and shafts, and is relatively stable. It is an excellent energy supply source. At the same time, medium- and large-scale wind power generation is widely used in power grid power supply, and the technology is relatively mature. Moreover, micro wind power generation system can provide energy for wireless sensors, which has a more in-depth research foundation in technology. Self-energy supply for wireless sensors can not only stably ensure the normal operation of sensors but also save a lot of line laying costs. When the micro wind power generation system is applied underground, it can also sense the wind speed to predict the occurrence of disasters. This paper aims to design a self-powered, flexible networking, and reliable micro wind power generation system and focus on the design of wind turbine with air duct, so as to provide suggestive guidance for establishing a more perfect mine self-powered monitoring sensor network in practical application.

According to the relative position between the rotating axis of the wind turbine and the ground, the wind turbine can be divided into horizontal axis type and vertical axis type.

Horizontal axis and VAWTs have their own advantages and disadvantages,\textsuperscript{29-31} mainly as follows:

1. The blade of horizontal axis wind turbine mostly adopts the design method of spiral or conical variable cross-section. Before the design of wind turbine, the blade airfoil should be designed, and the blade should be processed and manufactured into variable cross-section spiral, which is very difficult to design and manufacture. The blade of vertical axis wind turbine mostly adopts constant section airfoil.

2. The wind flow and direction are constantly changing. In order to maintain the best windward state, the windward device needs to be designed for the horizontal axis wind turbine. The blade of vertical axis wind turbine is perpendicular to the direction of wind flow, so the optimal power generation state can be realized without upwind device, which simplifies the mechanism of generator set and improves the stability of the system.

3. The horizontal axis wind turbine blade is connected with the motor by the hub, and one end is fixed, and the blade is in the suspended state. In particular, large and
super large wind turbines form a large bending moment due to their own gravity and aerodynamic force, which has a certain impact on the structural stability of the blade. The vertical axis wind turbine blades are mostly fixed at both ends, so the force on the blades is simple and easier to analyze.

4. Although vertical axis wind turbine has many advantages in mechanical structure and system stability, its biggest disadvantage and the most important factor affecting its development is its low wind energy utilization coefficient.

5. The vertical axis wind turbine is simpler in design and manufacturing than the horizontal axis wind turbine, but the vertical axis wind turbine has a small blade tip speed ratio, which leads to the low speed of the wind turbine. Therefore, it is necessary to add a speed increaser in the wind turbine and motor to make the motor run at high speed, which not only increases the complexity of the generator system but also reduces the stability of the system.

6. From the development history of horizontal axis and VAWTs, horizontal axis wind turbines have been applied on a large scale since the end of the 19th century, with a long development time. People have deep research on them, and the theory and technology are relatively mature. The research on vertical axis wind turbine started late, and its research is still in the research and exploration stage. There is no mature design concept and method, nor perfect product production system and standard.

To sum up, in order to improve the wind energy utilization of wind turbine as much as possible and make the wind turbine output more power, the type of wind turbine selected in this paper is horizontal axis wind turbine.

Due to the special shape of the air duct, the wind energy with low flow rate can be gathered, and the effect of speed-up rectification can be achieved. Under the condition of no additional energy consumption, the energy density can be improved by increasing the wind speed acting on the blade, which can not only effectively enhance the utilization rate of wind energy but also improve the low-speed start-up of the wind turbine, so as to maintain the continuous operation of the wind turbine.

2.1 | Design theory

The air duct in this design is the external air duct structure of small horizontal axis wind turbine, as shown in Figure 1. The energy accumulation principle of air duct can be obtained from the analysis of fluid continuity equation.\(^3\)

\[
T = \frac{1}{2} \rho C_T S U_\infty^2 R
\]

(1)

\[
P = \frac{1}{2} \rho C_P S U_\infty^3
\]

(2)

where \(C_T\) is the torque coefficient; \(\rho\) is the air density; \(S\) is the coverage area of the wind turbine impeller; \(R\) is the radius at the section; \(C_P\) is the power coefficient; and \(U_\infty\) is the wind speed flowing into the cross-section of the wind turbine impeller.

In this paper, the incompressible fluid model is adopted. According to the continuity equation of fluid, it can be seen that

\[
\overline{U}_1 S_1 = \overline{U}_2 S_2
\]

(3)

2.1.1 | Design theory

The principle of the air duct structure studied in this paper is due to the special shape of the air duct, the wind energy with low flow rate can be gathered, and the effect of speed-up rectification can be achieved. Under the condition of no additional energy consumption, the energy density can be improved by increasing the wind speed acting on the blade, which can not only effectively enhance the utilization rate of wind energy but also improve the low-speed start-up of the wind turbine, so as to maintain the continuous operation of the wind turbine. The wind speed underground is generally 2 ~ 8m / s. Under this wind speed, the wind turbine with air duct can provide effective energy supply.

2.1 | Air duct design

The principle of the air duct structure studied in this paper is due to the special shape of the air duct, the
where $\overline{U}_1, \overline{U}_2$ is the wind speed at the inlet of the air duct and the throat (at the impeller of the wind turbine); $S_1$ is the cross-sectional area of air duct inlet, and $S_2$ is the cross-sectional area of the throat of the air duct.

2.1.2 | Shape design of air duct

In order to gather more wind energy and accelerate the air flow, the air duct structure is designed according to the area of the air inlet greater than the air outlet. In addition, while accelerating the air flow, considering the relationship between the shape of the air duct and the wind acceleration effect, the linear air duct is selected, as shown in Figure 2.

2.2 | Design of horizontal axis wind turbine

2.2.1 | Blade radius

The design wind speed of the air duct is accelerated from 3 m/s to 4.3 m/s, and the ratio of the inlet and throat of the air duct is 2:1. Considering the special underground environment and roadway area, the space of wind turbine can be preset. The design inlet diameter is 0.42 m, the design throat diameter is 0.21 m, the blade radius is 0.1 m, and the hub radius is 0.005 m, as shown in Figure 3.

2.2.2 | Rated power design of wind turbine

The rated power of wind turbine can be seen from formula\(^3\):

$$ P = \frac{1}{2} \rho AV^3 C_P \eta_1 \eta_2 \quad (4) $$

where $P$ is the rated power; $\rho$ is the air density; $C_P$ is the power coefficient; $A$ is the swept area of impeller; $\eta_1, \eta_2$ is the product of transmission efficiency and electric efficiency; and $V$ is the wind speed at the front end of the blade.

2.2.3 | Tip speed ratio and blade number

Calculation formula of tip speed ratio:

$$ \lambda_0 = \frac{\omega R}{V} \quad (5) $$

According to the tip speed ratio theorem, equation (5) is applicable to wind turbine blades with stable wind speed. According to equation (5), the smaller the tip speed ratio, the higher the angular velocity of the impeller. Theoretically, the higher the wind speed, the higher the power generation performance of wind turbine. Generally speaking, the speed of large wind turbines is usually low. Under the same power output, small wind turbine has higher rated speed to ensure greater energy conversion efficiency. The tip speed ratio is usually 4 ~ 8. The tip speed ratio is determined by Table 1:

The wind turbine studied in this paper is a micro wind turbine. High speed is selected to ensure a certain wind energy utilization rate $\lambda_0 = 4$. When $\lambda_0 = 4$, the number of blades can be 3–5, but it should be considered that the more the number of blades, the higher the manufacturing
Because five blade wind turbine is more stable in operation and power output than three blade wind turbine, and five blades are mostly used in micro wind turbines at home and abroad, so the number of blades of this wind turbine is $N = 5$.

### 2.2.4 | Airfoil and its aerodynamic characteristic parameters

One of the core principles of airfoil selection is to select the airfoil with large lift drag as far as possible to improve the power generation efficiency of wind turbine. The working condition of the wind turbine designed in this paper is low Reynolds number, and the airfoil of the micro wind turbine blade is selected. Four typical NACA5505, BW-3, SG6043, and A18 airfoils are selected from the "low speed airfoil data summary," and the airfoil types are shown in Figure 4.

The optimal airfoil is selected by analyzing the lift drag ratio, thrust coefficient, and surface stability of four typical airfoils at low Reynolds number. Since the lift coefficient and drag coefficient are functions of the angle of attack and Reynolds number, it is a prerequisite to determine the appropriate Reynolds number, which is calculated by the Reynolds number formula, it can be seen that the Reynolds number of the micro wind turbine is about $2 \times 10^4$. Because NACA5505 airfoil has high lift drag ratio and stability at low Reynolds number, NACA5505 airfoil is selected as the design airfoil without air duct and the best angle of attack $\alpha = 8^\circ$. Figure 5 shows the force diagram of NACA5505 airfoil at the optimal angle of attack, and Figure 6 shows the three-dimensional relationship surface diagram of lift drag ratio and torque coefficient at different angles of attack.

### 2.3 | Basic parameters of air duct and wind turbine

According to the regulations of coal mine safety regulations, the maximum wind speed of air inlet roadway shall not exceed 8 m/s, and the average wind speed under the actual mine is about 3 ~ 4 m/s, so the inflow speed of wind turbine is set as 3 m/s. At the same time, the appearance parameters of air duct and wind turbine are designed based on the actual mine conditions. The basic
parameters of the air duct and the wind turbine without air duct are shown in Table 2.

The blade is divided into 20 blade element sections along the spanwise direction, and the geometric data such as blade root distance, chord length, torsion angle, and corresponding airfoil of each blade element section are obtained, as shown in Table 3. Because the blade has different characteristics on different leaf elements, the two-dimensional model cannot reflect the spatial structure of the blade. In this paper, the three-dimensional model of the blade is drawn based on the coordinate transformation method.

3 | AERODYNAMIC PERFORMANCE ANALYSIS OF WIND TURBINE WITH AIR DUCT

3.1 | 3D solid modeling of wind turbine

The three-dimensional space coordinate value is obtained based on the coordinate change, and the three-dimensional model of the wind turbine impeller is established, as shown in Figure 7. The blade is one of the core components of wind turbine impeller. The material of blade, the design of airfoil, and the structural form of blade directly affect the performance and efficiency of wind turbine generator. The aerodynamic design theory of wind turbine generator blade is developed on the basis of wing aerodynamic theory. The classical blade design theories include Bates theory, simplified wind turbine theory, momentum theory, Wilson aerodynamic design theory, and Glauert ring momentum theory, etc. When the wind turbine rotates, the inner basin is a compressible and viscous unsteady flow field, and the motion of wind flow is very complex. The blade surface belongs to complex twisted surface. Through three-dimensional modeling and simulation of blades, the geometric parameters and aerodynamic characteristic parameters of blade airfoil can be deeply studied to the greatest extent.

The three-dimensional model of the air duct is combined with the three-dimensional model of the wind turbine according to the optimal parameters. As shown in Figure 8, the wind turbine is installed at the minimum section at the outlet of the air duct.

3.2 | Flow field simulation of wind turbine

Based on the three-dimensional structure of the wind turbine of the air duct, the external flow field model is established, as shown in Figure 9. The cylindrical flow field is used as the calculation domain of the whole flow field, and the position of the impeller rotation center is defined as the coordinate origin. The whole calculation domain of the wind turbine is composed of inner basin and outer basin, in which the inner basin represents the flow field inside the air duct and the wind turbine, and the outer basin represents the natural wind field of the external environment. The total length of the whole outflow field is 5 m, and the outer basin radius is 1 m.
3.3 | Meshing

Unstructured grid is adopted for calculation, and the three-dimensional geometric model is imported into the preprocessing software meshing for grid division. The overall grid model is shown in Figure 10. Due to the complex flow field characteristics of wind turbine blades during rotation, it is necessary to encrypt the inner watershed grid to meet the calculation accuracy, and re-encrypt it at the blade hub interface. The whole flow field model is meshed with 12152010 elements and 20455770 nodes.

3.4 | Turbulence equation

Solving complex fluid flow problems usually requires a two-equation model, which can be divided into k-ε model and k-ω model. SST (shear stress transfer) k-ω model integrates the advantages of standard k-ω model, and standard k-ε model. SST k-ω model has the advantages of far-field calculation, can accurately predict the fluid flow, and can also predict the fluid separation under the condition of reverse pressure gradient. It has advantages for reverse pressure gradient flow and airfoil calculation. When the wind turbine rotates, the inner basin is a compressible and viscous unsteady flow field, and the motion of the wind flow is very complex. The turbulence model suitable for the characteristics of the flow field around the wind duct and the wind turbine should be selected through fluent calculation. Due to the small gap (1 mm) between the wind turbine blade and the air duct, the turbulence in the air duct is complex, so the turbulence equation of the flow field adopts SST k-ω two equation turbulence model, where k represents the turbulent kinetic energy in the model, ω represents the turbulent dissipation rate in the model. The SST k-ω model has good stability, convergence accuracy, and high calculation efficiency in the near wall region. Its control equations are as follows:²⁰
Turbulent kinetic energy transport equation:

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j} \left[ \rho u_j k - (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] = \tau_{ij} S_{ij} - \beta^* \rho \varepsilon k \tag{6}
\]

Turbulent dissipation rate equation:

\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_j} \left[ \rho u_j \varepsilon - (\mu + \sigma_\varepsilon \mu_t) \frac{\partial \varepsilon}{\partial x_j} \right] = P_\varepsilon - \beta \rho \varepsilon^2 + 2(1 - F_1) \frac{\rho \sigma_\varepsilon}{\rho \sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \frac{\partial \rho \varepsilon}{\partial x_j} \tag{7}
\]

3.5 Boundary conditions and solver settings

The boundary conditions mainly include inlet and outlet boundary conditions, wall conditions, internal element area, and surface boundary conditions. The main boundary conditions set in this paper are:

1. Speed inlet: set the inlet to velocity inlet, and set the speed to 3 m/s;
2. Free exit: set outlet to outflow;
3. Interface condition: because the grid size of internal and external watersheds is inconsistent, the interface of internal and external watersheds is set as interface boundary condition and paired.

The software ANSYS FLUENT is used for numerical simulation. The solution is solved by a three-dimensional separation implicit solver. SIMPLE algorithm, PRESTO scheme, and Second-Order Upwind scheme are adopted for the solution. The implicit separated pressure basis is used for solution, the SIMPLE algorithm is used for velocity and pressure coupling, and the Second-Order Upwind scheme is used for discrete scheme. The residual is controlled in the order of 10^{-4}, and the number of iterations converges to 5000.

4 Analysis of simulation results for wind turbine with air duct

4.1 Analysis of velocity and pressure distribution in outer basin

It can be seen from Figure 11 that when the incoming flow passes in front of the air duct, the speed is reduced to a certain extent due to the obstruction of the air duct. When it flows into the air duct, the air is accelerated and rectified, and the speed increases near the impeller. After passing through the impeller, a certain range of low-speed...
zone is formed behind the impeller, and the speed is the lowest near the impeller rotating shaft, and gradually increases along the radial direction. Due to the centrifugal force generated by the rotation of the impeller, the wake expands downstream of the impeller and increases the width of the wake area, which does not increase after 3 times the impeller diameter and integrate with the incoming flow. In this process, the velocity of the wake flow field gradually decreases with the increase of the axial distance. When the impeller diameter is 7 times, the velocity of the center line in the wake region gradually increases with the increase of the axial distance and merges with the wind flow of the outflow field.

It can be seen from Figure 12 that due to the diversion and obstruction of the air duct, the wind pressure of the air flow in the front section of the air duct increases and reaches the maximum value at the inlet of the air duct. After the air flow enters the air duct structure, the pressure value at the front end of the blade is the maximum, the pressure value at the rear end of the blade is the minimum, forming a negative pressure, and a certain range of negative pressure area is formed at the rear end of the impeller, which is very beneficial to the effective operation of the wind turbine.

4.2 | Analysis of velocity and pressure distribution in inner basin

Figure 13 shows the cloud diagram of the air velocity distribution at the front and rear of the impeller and at the center of the blade. It can be seen that the velocity distribution generally tends to increase gradually along the radial direction from the center position, and the velocity is low at the extreme edge. This is mainly due to the viscous action and friction between the air and the air duct, resulting in the rapid reduction of the wind speed.

Figure 14 shows the pressure distribution at the front end, center, and rear end of the impeller, respectively. It can be clearly seen from the figure that the pressure on the windward side of the whole wind wheel is greater than that on the leeward side. The maximum pressure appears on the hub and blade surface. On the windward side of the blade, the flow rate decreases rapidly due to the obstruction of the air flow, and the pressure on the blade surface is basically positive pressure. On the leeward side of the blade, most of the pressure is negative pressure due to the increase of the air flow rate. The relatively high pressure area is concentrated near the stagnation point of the leading edge of the blade, the pressure in the blade root area is low, and the pressure gradient is small. This is because the air flow on the blade surface rotates with the blade to produce centripetal acceleration, and the centripetal force is provided by the radial static pressure difference. Therefore, the static pressure changes into a negative reverse pressure gradient from the blade root to the blade tip.

Comparing the air velocity distribution cloud map and pressure distribution cloud map in Figures 13c and 14c, it is found that there is a great difference from the velocity and pressure distribution at 20 mm in front of the impeller. This is mainly because when the air flow passes through the impeller, part of the wind energy acts on the blade and convert it into rotating mechanical energy. However, due to the restriction of the air duct, the wind flow of the wind turbine with the air duct cannot quickly spread around, so that the excess energy after the impeller rotates can only flow out through the blade gap, and the outflow area is small. According to the continuity principle, the wind
speed and pressure of the blade gap in Figure 14c increase, but after the wind flow is separated from the air duct, the speed and pressure of the air gradually merge with the outer basin.

4.3 Cloud analysis of blade pressure distribution

It can be seen from Figure 15 that the relative pressure on the windward side of the blade is positive and the relative pressure on the leeward side is negative, which indicates that the windward side of the blade is the pressure surface and the leeward side is the suction surface. Due to the existence of this pressure, the pressure on both sides of the blade is different, which makes the blade to rotate and generate lift to drive the impeller to rotate.

Figure 16 shows the pressure distribution cloud diagram of different sections of the blade. It can be seen that the pressure on the windward side and leeward sides of the blade changes gently along the airfoil curve, which is due to various curvatures at different positions and various forces at different positions of the airfoil, resulting in changes in the pressure. It can also be seen that the aerodynamic performance of the blade root is poor, which is mainly used to ensure the strength. At 0.7 R~0.9 R of the blade tip, the maximum pressure on the windward side is close to 14.83 MPa and the minimum pressure on the leeward side. Therefore, this position can provide more lift, with good aerodynamic performance, and the blade can generate large rotating power. From the cross-sectional pressure distribution cloud diagram, it can be seen that the pressure on the leeward side diffuses outward with the middle of the airfoil as the negative pressure center.

5 STUDY ON PERFORMANCE OF WIND TURBINE WITH AIR DUCT

5.1 Performance analysis of wind turbine under different wind speeds

In order to fully understand the aerodynamic performance characteristics of the wind turbine under different working conditions, set the wind turbine under different working conditions for simulation calculation, comprehensively evaluate the aerodynamic performance of the wind turbine, and improve the basis for the performance optimization and structural parameter improvement of
the wind turbine. The working condition parameters are shown in Table 4.

Figure 17 is the power curve of wind turbine at different speeds. As can be seen from Figure 17, the power of wind turbine increases with the increase of wind speed. When the wind speed is lower than 1.40 m/s, the power is almost maintained at a very low level, which can be regarded as that the wind turbine fails to operate effectively, indicating that the aerodynamic wind speed of wind turbine is 1.40 m/s. Figure 18 is the torque curve of wind turbine at different speeds. As can be seen from Figure 18, the starting torque is 0.001 N.m. When the wind speed increases by 2.80 m/s, the power and torque of the wind turbine increase rapidly. This is because the design rated wind speed of the wind turbine is 3.0 m/s. After the wind speed reaches or approaches the rated wind speed of the wind turbine, the advantages of the wind turbine model are reflected, and the power and torque increase rapidly. Then, with the increase of wind speed, the output power of the wind turbine increases steadily. This shows that the wind turbine can maintain stable operation after meeting the starting torque and can provide effective power generation to meet the power consumption requirements of the sensor.

At the same time, it can be seen that the wind speed actually acts on the front end of the wind turbine impeller (rotating domain inlet) under the working conditions of wind farm wind speed of 0.7 m/s, 1.40 m/s, 2.10 m/s, 2.80 m/s, and 3.50 m/s. The results are shown in Table 5.

Figure 19 shows the fitting curve between the flow field velocity and the impeller front-end velocity. The fitting linear slope is expressed as the magnification of the wind turbine, and the wind speed magnification is 2.03, that is, when the wind speed of the external flow field is \( v \), the actual speed acting on the blade is 2.03 \( v \).

### 5.2 Performance analysis of ducted wind turbine with different airfoils

The aerodynamic characteristics on ducted wind turbines with different airfoils are selected and analyzed to verify...
the reliability of airfoil selection in the design stage. In this paper, three airfoils BW3, SG6043, A18 with similar airfoil structure to NACA5505 are selected from the "low speed airfoil data summary" to design the airfoil ofducted wind turbine, select the air duct with the same structure, and design and optimize the optimal angle of attack, chord length and other parameters of the airfoil. The ratio of inlet diameter to throat diameter is defined as B, i.e. $B = \frac{L_1}{L_2}$. The relevant parameters of each scheme are shown in Table 6.

Power coefficient, torque coefficient, and thrust coefficient are three key indexes to measure the performance
of wind turbine. Figures 20 and 21 are the curve diagram of the performance index of each airfoil air duct scheme with the change of tip speed ratio.

Figures 20 and 21 show that:

1. F0 model: when the tip speed ratio is 4, the rated speed of the wind turbine reaches 224 rad / s, and the wind turbine reaches the maximum power coefficient value. F1 model: when the tip speed ratio is 4.3, the rated speed is 240.8 rad / s, and the wind turbine reaches the maximum power coefficient. F2 model: the maximum power coefficient corresponding to the tip speed ratio of 4.15. In F3 model, when the tip speed ratio is between 4 and 5, the maximum power is stable, but the maximum power coefficient is small, only 0.12.

2. When the tip speed ratio is between 1 and 3, the torque coefficient of F0 model is maintained at a
high level compared with F1 model, F2 model, and F3 model. At the same time, the curves of F2 model and F3 model are basically consistent in this interval, indicating that the performance of the two models is consistent at low tip speed ratio. After the tip speed ratio is more than 3, the rise speed of the F2 model is significantly faster. When the tip speed ratio is 4.3, the maximum torque coefficient is 0.062, but the maximum torque coefficient of the F3 model is 0.025. It shows that the F2 model has a very obvious advantage.

The thrust coefficient curve of different airfoils with tip speed ratio is shown in Figure 22. The thrust coefficient increases slowly with the increase of tip speed ratio, and then increases rapidly, and finally maintains at a high level. However, the thrust coefficient of the F0 model is large at low tip speed ratio, indicating that the F0 model can ensure the stable and sustainable operation of the wind turbine at low speed.

From the above analysis, it can be seen that it is not the higher the tip speed ratio and wind turbine speed, the better. When the wind turbine reaches the optimal speed, with the increase of wind turbine speed, the flow resistance of fluid increases and the blade path is blocked. At the same time, the wind pressure of wind turbine also decreases rapidly, the power coefficient and torque coefficient decrease rapidly, and the thrust coefficient cannot rise.

In order to demonstrate the validity and utility of the current numerical simulation, the numerical results are compared with the experimental results of reference. The detailed parameter information for the wind turbine is shown in Table 7. The design variables for the parameterization are shown in Figure 23. A verification comparison has been made between the current calculation results and the corresponding experimental results of Aii-type wind turbine obtained by Ohya et al. in 2010, as shown in Figure 24. The results show that there is an acceptable consistency between the experiment and the current CFD for the target function by using SST k-ε turbulence model to make quantitative and qualitative analysis of power efficient. The variation trend of power coefficient with tip speed ratio obtained by the current numerical simulation is consistent with the experiment, and the corresponding value is also very close. Therefore, our calculation model is accurate and reliable.

6 | PERFORMANCE ANALYSIS OF WIND TURBINE WITHOUT AIR DUCT

In the same flow field, the wind flow accelerated and integrated by the air duct has the characteristics of high speed and uniform distribution. In order to better illustrate the
advantages of air duct, ANSYS FLUENT is used to simulate the aerodynamic performance of wind turbine without air duct, and the flow field characteristics under two different states are compared to verify whether the air duct plays a substantive role in improving the power of wind turbine.

6.1 Grid division

First, the outer basin and inner basin of the wind turbine model are divided in Solidworks, and then they are imported into meshing for grid division, as shown in Figure 25. The fluid calculation domain, meshing, and calculation method of the wind turbine without air duct are consistent with those in Section 2, and the inlet wind speed is set to be 3 m/s.

6.2 Analysis of simulation results

After about 3000 iterations, the errors of residual error and torque are less than the set value, and the calculation results tend to be consistent. The flow field, the air flow, and pressure distribution around the blade are analyzed by ANSYS FLUENT post-processing program.

6.2.1 Comparison of velocity and pressure contours of flow field

It can be seen from Figures 26 and 27 that due to the absence of the obstruction of the air duct, a large velocity gradient is not formed at the front end of the blade, and the wake area generated by the rotation of the blade is large, indicating that the wind turbine without the duct structure has poor effect on wind energy conversion.

It can be seen from Figures 28 and 29 that the pressure gradient of the wind turbine without air duct structure is small and no large pressure difference is formed, indicating that the utilization rate of wind energy by the wind turbine is low. At the same time, no effective pressure gradient is formed before and after the blades, which may lead to blade shutdown, unsustained operation of the wind turbine, and affecting the energy supply of the sensor.
6.2.2 | Comparison of blade pressure and velocity contours

It can be seen from Figures 30 and 31 that the force on the blade of the wind turbine without the air duct varies little from the blade root to the blade tip, with the maximum value of about 11.78 Pa and the minimum value of 6.5 Pa. For the wind turbine with the air duct structure, the force on the blade root is relatively small, and the force on the blade tip is relatively obvious. As shown in Figure 30a, in the red region, the pressure here is about 14.83 Pa, which is greater than that without the air duct. Under the action of the air duct, the force on the blade tip increases significantly, which means that there is a large lifting force on the blade, so the blade with the air duct structure will also produce greater torque. This shows that under the same
working conditions, the blade with the air duct structure has a greater torque and a higher wind energy conversion rate.

6.3 Effect analysis of ducted wind turbine

Through the analysis and comparison of the force and wind speed of the wind turbine blade with and without air duct, it can be clearly seen that the force of the wind turbine blade with air duct is significantly greater than that without air duct, so that the torque of the blade to the wind turbine is also greater. However, the flow field analysis can only qualitatively analyze the force difference between wind turbine with air duct and without air duct and cannot quantitatively reflect the improvement of its power.

Figure 32 shows comparison of power with and without air duct. As can be seen from Figure 32, the power of the wind turbine without air duct structure is always at a low level compared with the wind turbine with air duct structure. In the range where the wind speed is lower than 2 m/s, the power difference between the two structures is not great because the torque generated below 2 m/s does not reach the starting torque of the wind turbine, that is, the wind turbine fails to operate effectively, and the function of the wind guide tube is not reflected. Then, with the
increase of wind speed, the advantages of air duct structure are reflected, and the difference of power is larger and larger.

7 | CONCLUSIONS

Considering the narrow underground space and the distribution of underground energy, it is decided to use the wind turbine with air duct for energy collection. The wind turbine can improve the utilization rate of wind energy and reduce the starting wind speed of wind turbine under the condition of unchanged size. By designing the wind turbine structure and optimizing the key parameters, the wind turbine suitable for the special underground environment is obtained. The aerodynamic performance of wind turbine is analyzed. Compared with the wind turbine without air duct, the wind turbine with air duct has higher wind energy conversion and output power under the condition of low Reynolds number, which verifies the feasibility of wind turbine with air duct.

1. The wind turbine with air duct disturbs the external flow field and changes the speed of incoming flow into the air duct. The air duct structure rectifies and accelerates the wind flow in the outer basin, so that the quality of wind energy reaching the front end of the blade is high, which is beneficial to improve the utilization rate of wind energy.

2. When the rated wind speed is 3 m / s, the power and torque of the wind turbine increase rapidly. With the increase of wind speed, the output power of wind turbine increases steadily. When the wind speed is 1.40 m / s lower than the starting wind speed, the wind turbine fails to operate effectively. When the wind speed is higher than the starting wind speed, the wind turbine can operate continuously and stably and output effective power.

3. Compared with other airfoils, NACA 5505 airfoil has higher lift drag ratio and thrust coefficient, which is very suitable for underground low-speed wind. The correctness of airfoil selection in the design stage is verified.

4. The wind turbine without air duct structure has poor wind energy conversion effect and low utilization rate of wind energy. At the same time, there is no effective pressure gradient before and after the blade, which will lead to the unsustainable blade rotation of the wind turbine and affect the energy supply of the sensor. The blade with air duct structure has large torque and high wind energy conversion rate. Under the condition of low Reynolds number, the power generated by the wind turbine with air duct structure is three times that of the wind turbine without air duct structure. Compared with the wind turbine without air duct structure, the wind turbine with air duct structure is more suitable for the environment with narrow space and low wind speed and can output higher power.

In recent years, with the progress of intelligent mining technology, more and more wireless monitoring equipment and systems are built in the underground roadway of coal mine to meet the increasing demand of safety monitoring. However, different from the ordinary coal mine underground roadway, the underground working face is an environment that develops dynamically with the mining progress. The wireless node can only run by the battery. Once the node is arranged, the battery cannot be replaced due to the poor environment, resulting in a very short service life of the wireless network. Aiming at the disadvantage of low efficiency of breeze wind turbine, this paper proposes an improved wind turbine, namely wind turbine with air duct, and demonstrates and calculates the feasibility of applying the breeze power generation system underground. The designed wind turbine with air duct can supply effective energy, convert wind energy into stable electric energy through technology, and provide energy for the sensor system, which can greatly solve the dilemma faced by wireless sensors and provide a scientific basis for the development of intelligent mining and unmanned working face.

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CONFLICT OF INTEREST
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REFERENCES
1. Yadav DK, Mishra P, Jayanthu S, et al. On the application of IoT: slope monitoring system for open-cast mines based on LoRa wireless communication. Arab J Sci Eng. 2021;184:1-12.
2. Mahdavipour O, Mueller-Sim T, Fahimi D, et al. Wireless sensors for automated control of total incombustible content (TIC) of dust deposited in underground coal mines. In: IEEE Sensors. IEEE. 2015:1-4.
3. Alfonso I, Goméz C, Garcés K, et al. Lifetime optimization of Wireless Sensor Networks for gas monitoring in underground coal mining. In: 7th International Conference on Computers Communications and Control (ICCCC). IEEE; 2018:224-230.
4. Nimkar AV, Salunke AV. Fire contour approximation algorithm for bord-and-pillar coal mine: revisited. In: IEEE Sensors Applications Symposium (SAS). IEEE; 2018:1-6.
5. Karimian SMH, Abdolahifar A. Performance investigation of a new darrieus vertical axis wind turbine. Energy. 2020;191:116551.
6. Takwa S, Sana J, Hanen B, et al. Finite volume free vibration analysis of a new aerodynamic styling wind turbine. Wind Eng. 2018;42(5):397-410.
7. Govind B. Increasing the operational capability of a horizontal axis wind turbine by its integration with a vertical axis wind turbine. Appl Energy. 2017;199:479-494.
8. Tian W, Ozbay A, Hui H. An experimental investigation on the aeromechanics and wake interferences of wind turbines sited over complex terrain. J Wind Eng Ind Aerodyn. 2018;172:379-394.
9. Wang W, Matsubara T, Junfeng H, et al. Experimental investigation into the influence of the flanged diffuser on the dynamic behavior of CFRP blade of a shrouded wind turbine. Renewable Energy. 2015;78:386-397.
10. Lipian M, Dobrev I, Karczewski M, et al. Small wind turbine augmentation: experimental investigations of shrouded- and twin-rotor wind turbine systems. Energy. 2019;186:15855.
11. Hassanpour M, Azadani LN. Aerodynamic optimization of the configuration of a pair of vertical axis wind turbines. Energy Convers Manage. 2021;238(8):114069.
12. Li S, Li Y, Yang C, et al. Investigation of solidity effect on the power output of dual vertical axis wind turbines in urban environment. Energy Convers Manage. 2021;229:113689.
13. Saulescu R, Neagoe M, Jaliu C, Munteanu O. A comparative performance analysis of counter-rotating dual-rotor wind turbines with speed-adding increasers. Energies. 2021;14:2594.
14. Verma N, Beena D. Influence of Reynolds number consideration for aerodynamic characteristics of airfoil on the blade design of small horizontal axis wind turbine. Int J Green Energy. 2021. doi:10.1080/15435075.2021.1960356
15. Barnes A, Marshall-Cross D, Hughes BR. Towards a standard approach for future Vertical Axis Wind Turbine aerodynamics research and development. Renew Sustain Energy Rev. 2021;148:111221.
16. Lee HM, Kwon OJ. Performance improvement of horizontal axis wind turbines by aerodynamic shape optimization including aeroelastic deformation. Renewable Energy. 2019;147:2128-2140.
17. Altaee A, Khlaifat N, Zhou J, et al. Optimization of a small wind turbine for a rural area: a case study of Deniliquin, New South Wales, Australia. Energies. 2020;13:2292.
18. Wu X, Lee DW. An electromagnetic energy harvesting device based on high efficiency windmill structure for wirelcss forest fire monitoring application. Sens Actuators, A. 2014;219(10):73-79.
19. Agha A, Chaudhry HN, Wang F. Diffuser augmented wind turbine (dawt) technologies: a review. Int J Renew Energy Res. 2018;8(3):1369-1385.
20. Abe K, Nishida M, Sakurai A, et al. Experimental and numerical investigations of flow fields behind a small wind turbine with a flanged diffuser. J Wind Eng Ind Aerodyn. 2005;93(12):951-970.
21. Ohya Y, Karasudani T, Sakurai A, Abe K-I, Inoue M. Development of a shrouded wind turbine with a flanged diffuser. J Wind Eng Ind Aerodyn. 2008;96(5):524-539.
22. Ghazalla RA, Mohamed MH, Hafiz AA. Synergistic analysis of a Darrieus wind turbine using computational fluid dynamics. Energy. 2019;189(12):206-214.
23. Chen L, Ponta FL, Lago LI. Perspectives on innovative concepts in wind-power generation. Energy Sustain Dev. 2011;15(4):398-410.
24. Werle MJ, Presz WM. Ducted wind/water turbines and propellers revisited. J Propul Power. 2015;24(5):1146-1150.
25. Li Y. On the definition of the power coefficient of tidal current turbines and efficiency of tidal current turbine farms. Renewable Energy. 2014;68:868-875.
26. Babar J. Theoretical framework to surpass the Betz limit using unsteady fluid mechanics. Phys Rev Fluids. 2020;5:022501-022507.
27. Klaptoz VR, Rawlings GW, Nabavi Y, Alidadi M, Li Y, Calisal SM. Numerical and experimental investigation of a ducted vertical axis tidal current turbine. In: Proceedings of the 7th European wave and tidal energy conference 1. 2007:1-6.
28. Guo W, Kang HG, Chen B, et al. Numerical and experimental study of the 3D effect on connecting arm of vertical axis tidal current turbine. China Ocean Eng. 2015;30(1):83-96.
29. Dawei L. Discussion on structure and classification of wind turbine. Prog Technol. 2018;217(04):56.
30. Zhengmao D. Experiment and Research on 50 W Street Lamp Wind Turbine. Inner Mongolia Agricultural University; 2009:1-6.
31. Fengyi Y, Jing W, Zebin D., et al. Structural mechanical characteristics analysis of lattice vertical axis wind turbine. Power Construct. 2008;29(11):67-70.
32. Alidadi M. Duct Optimization for A Ducted Vertical Axis Hydro Current Turbine. The University of British Columbia; 2009.
33. Zhu SQ, Xi FH, Gao JN. Aerodynamic optimization design and three-dimensional modeling of horizontal axis wind turbine blades. Contemporary Tourism. 2018;09:132-139.
34. Gray A, Singh B, Singh S. Low wind speed airfoil design for horizontal axis wind turbine. *Mater Today Proc.* 2021;2:341-250.

35. Li X, Zhang L, Song J, et al. Airfoil design for large horizontal axis wind turbines in low wind speed regions. *Renewable Energy.* 2020;145(1):2345-2357.

36. Ohya Y, Karasudani T. A shrouded wind turbine generating high output power with wind-lens technology. *Energies.* 2010;3(4):634-649.

37. Ohya Y, Uchida T, Karasudani T, Hasegawa M, Kume H. Numerical studies of flow around a wind turbine equipped with a flanged-diffuser shroud using an actuator-disk model. *Wind Energy.* 2012;36(4):455-472.

38. Khamlaj TA, Rumpfkeil MP. Analysis and optimization of ducted wind turbines. *Energy.* 2018;162:1234-1252.

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