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Flow Field Analysis and Structural Optimization of a Rotating Wind Collection Device

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ABSTRACT

In this paper, a new type of wind collection device that can generate rotating wind for wind power generation has been designed to address the shortcomings of current wind power generation devices. This device can collect wind energy from different directions by changing the direction of the wind. Firstly, the simulation model for this wind collection device had been designed by the software SolidWorks. Secondly, the internal flow field of the model was modeled and simulated using Computational Fluid Dynamics, and the k-ω SST model was selected in Fluent for flow field analysis. The results showed that this device could generate an outlet wind speed of 3.8 m/s at a wind speed of 4 m/s, which verified the wind collection effect of the device. Thirdly, the outlet wind speed was taken as the optimization objective, and orthogonal optimization design was carried out on the guide convex groove in the model, and the optimal design parameters of the guide convex groove were determined. The results showed that when the width of the diversion convex groove is 47.35mm and the height is 10.65mm, the outlet wind speed is the highest, about 3.89m/s. Finally, to verify the analysis results of numerical simulation, the experimental verification of the wind collection device was carried out through physical prototypes. The results indicated that the simulation results are consistent with the physical results The design of this device can provide theoretical support for the subsequent design of a full-direction wind collection device to cope with the complex wind direction conditions.

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INTRODUCTION

Offshore wind turbine is a technology that can use ocean wind energy for wind power generation. It has higher wind speeds and can produce more electricity than onshore wind turbines. In recent years, as the global demand for clean energy continues to increase, the development of offshore wind turbines is also increasing rapidly. As of 2023, offshore wind power generation has been widely used and developed worldwide. Large-scale offshore wind power projects have been built and operated in many countries and regions, and some of them have already been commercialized.

In recent years, with the continuous development of technology, the requirements for the stability, safety and economy of offshore wind power plants are constantly improving. In the future, offshore wind power will become one of the important sources of clean energy, while promoting the transformation of the global energy structure. In general, as an important form of marine energy, offshore wind power has broad development prospects, but at the same time, the technical, economic and environmental challenges that need to be overcome are gradually increasing. In the future, with the continuous improvement of offshore wind power technology and the gradual maturity of the market, the development prospects of this field are expected.

Wind turbines can be classified by shaft type, there are two main types: horizontal axis wind turbines and vertical axis wind turbines.

The development of horizontal axis wind turbines has been relatively mature, and domestic and foreign

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scholars have done corresponding research on the aerodynamic performance of horizontal axis wind turbines, the hydrodynamic performance of floating foundation, the installation and control of fans and many other aspects (1–4).

Because of its special structural characteristics, vertical axis wind turbines have many advantages that horizontal axis wind turbines do not have:

1. It is prone to wind. Vertical axis wind turbines can work no matter from which direction the wind blows;
2. The generator height is low. Compared with the horizontal axis fan, the generator of the vertical axis fan can be installed at a lower place on the ground, and the production, installation, transportation and maintenance costs are lower.
3. More suitable for wind farm construction. Horizontal axis fans need to be installed at a large distance from each other to reduce the impact of wake effects. For vertical axis fans, the resulting wake can dissipate faster by combining two vertical axis fans that rotate in opposite directions. More fans can be installed in the same space to ensure the reasonable and full use of resources (5–10).

At present, the power generation efficiency of horizontal axis wind turbines is higher than that of vertical axis wind turbines, but horizontal axis wind turbines had certain requirements for wind direction. However, due to the limitations of research lag in structural aspects, vertical axis wind turbines cannot be scaled up and commercialized. Therefore, this paper designed a wind collection device that can convert wind from multiple wind directions into vertical wind, enabled it to simultaneously have the characteristics of multi-directional wind reception for vertical axis wind turbines and high power generation efficiency for horizontal axis wind turbines.

Wind speed is one of the most important parameters to improve the efficiency of wind turbines. How to improve the wind speed of turbine blades is one of the key points of the researchers? Increasing the wind speed flowing through the blade increases its power generation and also improves the utilization of wind energy. So, the researchers focused on the study of wind collecting devices (11–16).

In 2012, Guo et al. (17) designed and studied a wind collecting hood system and its corresponding tower system, and used the reverse principle and Fluent software to analyze the wind flow blown by it, obtain the velocity cloud map at the exit, and verify its function in theory. Li (18) proposed a new type of mobile wind collector in 2013. When the wind speed is low, the device accelerates the wind flow in the shrinking tube, which not only increases the wind energy density, but also reduces the starting wind speed of the wind turbine. When the wind speed is large, the contractionary tube of the device moves backward along the track under greater wind pressure, and the wind speed increases less at the wind turbine in the device, so that the wind turbine can continue to work normally. Cai and Xiao (19) designed a ring wind collecting device which can transform the natural horizontal wind in any direction into the wind flowing clockwise along the ring to improve the power coefficient of the vertical axis wind turbine, and concluded that the device can improve the power coefficient and enable the wind turbine to have accurate angle of attack and better starting performance. Li et al. (20) researched and designed an innovative truncated-cone-shaped wind gathering device (WGD) which could be installed up and down of the rotor was proposed to collect more incoming flow and increase wind speed. They obtained two better structural parameter combinations of WGD and designed the model of the two kinds of WGD. The new WGD was proved to be effective for both the static and dynamic performance improvement of SB-VAWT. Gornatti (21) researched and designed a wind collection device for energy production consisting of a fixed external structure formed by a vertical cylinder having two bases (upper and lower), variable in height and diameter, with vertical partitions distributed along a circumference and equidistant to form nozzles that concentrate and direct the wind; At least one turbine is arranged in concentric form within the structure, including a rotating shaft maintained between the base and associated with the upper and lower bearings, on which a plurality of radial blades are fixed to transmit this motion to a complementary transmission device supported by at least a generator.

In this paper, a wind collecting device that can generate rotating wind is studied. At present, the power generation efficiency of horizontal axis wind turbines is higher than that of vertical axis wind turbines, but horizontal axis wind turbines had certain requirements for wind direction. However, due to the limitations of research lag in structural aspects, vertical axis wind turbines cannot be scaled up and commercialized. Therefore, this paper designed a wind collection device that can convert wind from multiple wind directions into vertical wind, enabled it to simultaneously have the characteristics of multi-directional wind reception for vertical axis wind turbines and high power generation efficiency for horizontal axis wind turbines (22–25). In the next part, the structure and simulation analysis of the device are introduced. The design parameters of the diversion groove of the device are optimized by means of orthogonal optimization design. The physical model of the device is introduced, and the results of the simulation model are verified by the physical model.

MATERIAL AND METHODS

Structure and numerical simulation of wind collecting device

Design scheme of wind collecting device

Figure 1 shows the designed wind collecting device. The overall structure of the device is composed of a wind inlet plate, a swirl plate, a small blade moving plate, a large blade moving plate and a wind collecting pipe. The main body of the device is composed of three semi-conical vortex plates with the same structure, which are fixed and connected to each other. The lower end of the three coiling plates is provided with wind outlets, and the angles of the movable plates of the large blades are adjustable according to the wind speed. The three vortex plate outlets are fixed and connected with the wind collector. The wind collecting pipe can be designed into straight pipe or bent pipe according to the situation. In this device, the wind is composed of two parts. One is the main wind intake baffle area at the top, which is the main power source of the device, and the internal inclination Angle can be adjusted through the control system. The inner wall of the wind intake baffle is designed with a diversion channel, and the effect is that the natural wind force immediately rotates along the diversion channel after entering the device and outputs horizontally along the wind collecting pipe (straight pipe is vertical). Think of it as a rifle in a barrel. The second is that the small window opened in the device also has wind entry, which has two main functions. The time difference between the wind inlet of the small window in the middle and the main wind inlet plate can strengthen the rotational kinetic energy of the wind. In order to solve the situation of unstable wind speed, the wind volume control system adopts a negative feedback program to automatically adjust the Angle of the large blade moving plate and the small blade moving plate, so as to adjust the wind volume to ensure that the impeller maintains a relatively stable speed, and automatically adjust the Angle to reduce the pressure of the main body of the device when encountering extreme weather, but at this time the bottom wind collector still has wind output power. Therefore, in case of extreme weather such as typhoon, the device can still collect wind power and generate electricity normally.

Establishment of simulation model

The main purpose of the flow field simulation analysis is to study the aerodynamic characteristics of the pipeline flow field through CFD, and verify the wind collection effect and optimize the design of the wind collection device through the simulation results.

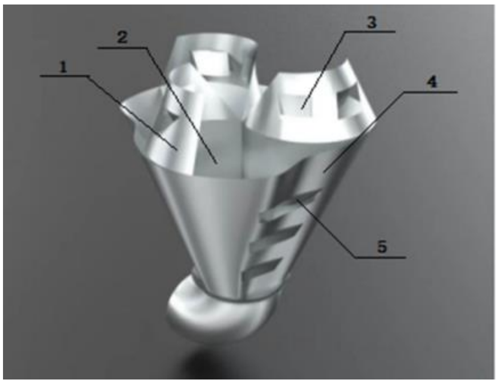
Geometric model parameters

In general, the more complex the shape and structure of the geometric model and the more parts contained within the model, the more grids are required when meshing the geometric model. In order to improve the grid quality, reduce the requirements of computing resources and computing time, and ensure the accuracy of calculation results, the geometric model should be simplified within the allowable range before establishing the grid model. In this way, the difficulty and quantity of grid division can be reduced by ignoring some small and unimportant geometric structures of the wind collecting device in the geometric model.

Computer software SolidWorks was used for modeling, and the whole was composed of wind intake plate, swirl plate (with built-in guide strip), spoiler and large blade movable plate. The specific structure is shown in Figure 2. The total height of the model is 1200mm, the height of the intake plate is 300mm, the inclination angle is 75, the height of the movable blade plate is 120mm, and the internal inclination angle is 35. It is shown in Figure 3

Grid division

The simplified model is imported into DesignModeler, set the length of the calculation domain to 5000mm, width to 5000mm, height to 3000mm, and set inlet 1, outlet 1 and outlet 2 at the inlet, as shown in Figure 4. The Workbench solver selects the fluid flow solver with fluent meshes,



1. wind intake plate; 2. Swirl plate; 3. Lobular movable plate; 4. Spoiler; 5. Large leaf movable board

Figure 1. Design structure of the wind collecting device

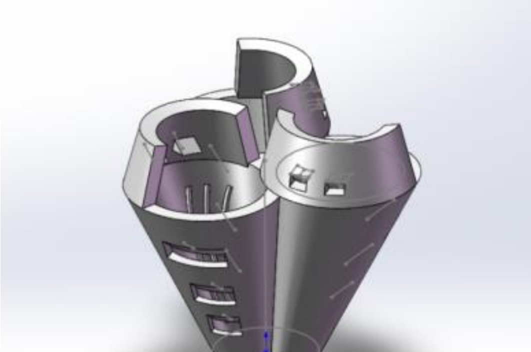


Figure 2. Simplified model

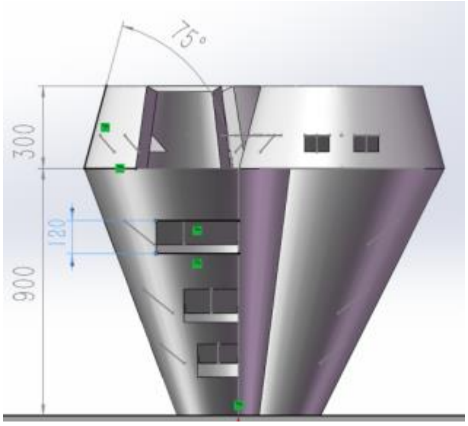


Figure 3. Dimensions

and the minimum size of the surface mesh is set to 2.5mm and the maximum size is set to 125mm. The surface mesh parameter is shown in Figure 5. Set inlet1 as velocity-inlet, outlet1 and outlet2 as pressure-outlet, the lower ground as ground, and the remaining boundary as wall. In order to reduce the computational pressure, polyhedra was selected as the volume mesh type. The volume mesh parameters are shown in Figure 6. The final volume mesh is shown in Figures 7, 8 and 9. The number of grids is about 660,000.

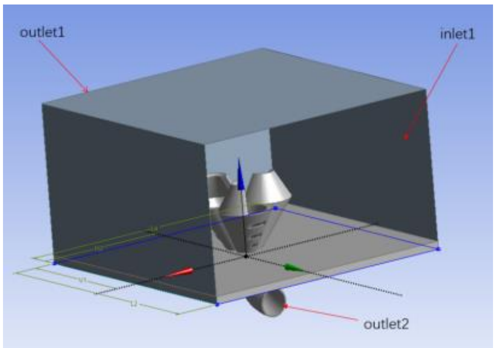
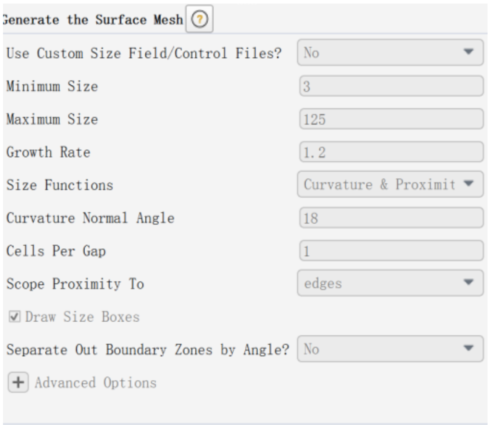


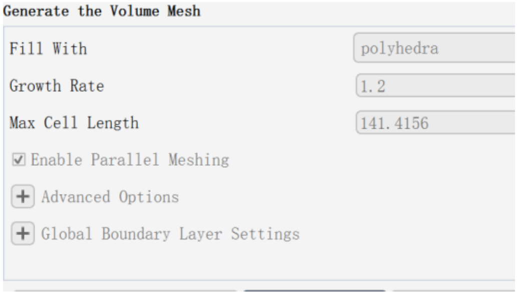
Figure 4. Compute domain and import and export



enerate the Surface Mesh

Use Custom Size Field/Control Files?	No
Minimum Size	3
Maximum Size	125
Growth Rate	1.2
Size Functions	Curvature & Proximit
Curvature Normal Angle	18
Cells Per Gap	1
Scope Proximity To	edges
☑ Draw Size Boxes	
Separate Out Boundary Zones by Angle?	No
+ Advanced Options	

Figure 5. Surface mesh parameters



Generate the Volume Mesh

Fill With	polyhedra
Growth Rate	1.2
Max Cell Length	141.4156
☑ Enable Parallel Meshing	
+ Advanced Options	
+ Global Boundary Layer Settings	

Figure 6. Volume mesh parameters

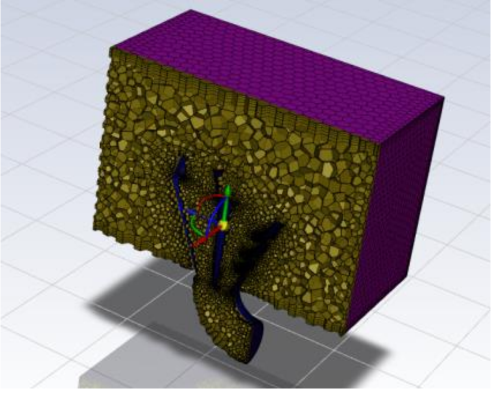


Figure 7. Body grid

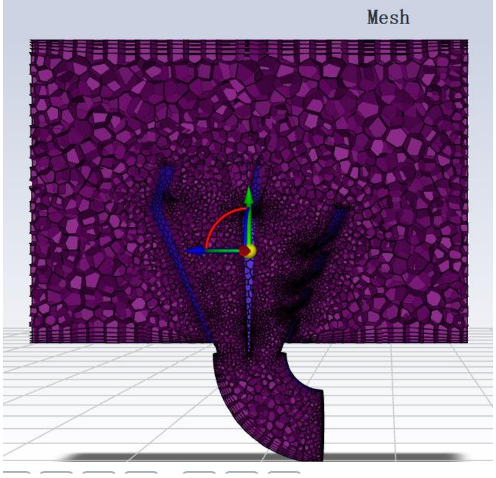


Figure 8. Cross Section of Volume Grid

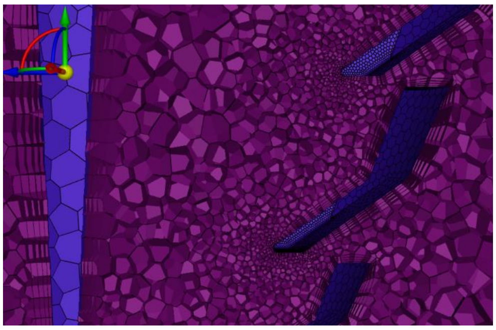


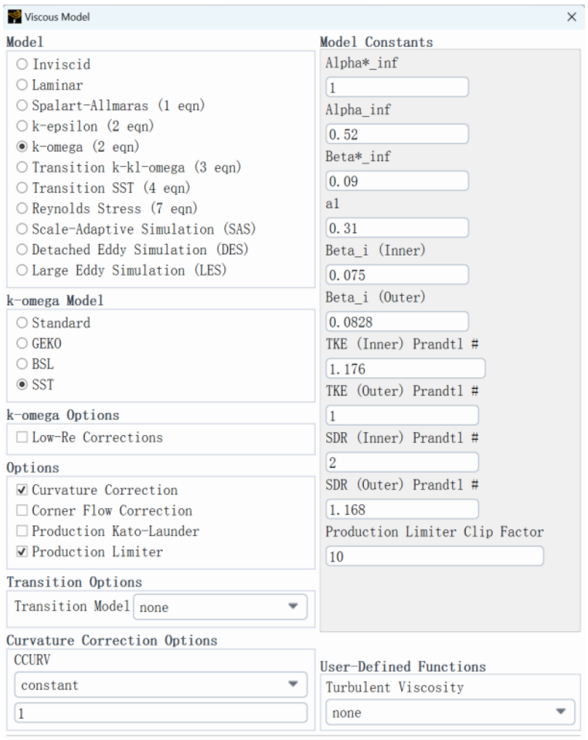
Figure 9. Partial Enlarged of Volume Grid

Fluent solves parameters

k-ωSST model is chosen for this solution. The model is a turbulence model based on Reynolds mean and Navier-Stokes equations, and is characterized by the addition of Shear Stress Transport (SST) to the standard k-ω model. This model not only synthesizes the advantages of k-ε model and k-ω model, but also overcomes their defects to a certain extent. The SST k-ω model has good numerical stability, and is closer to the physical experimental results, and can accurately calculate a variety of flow field problems from non-viscous conditions to small proportions near the wall. Therefore, the SST k-ω model is widely used in engineering practice, especially in the field of aerodynamics and fluid mechanics where the flow structure and turbulent boundary layer need to be calculated in detail. The fluid is air, the density is 1.225kg/m, and the dynamic viscosity is 1.7894*10kg/m. Aluminum is selected as a solid. Set the speed of inlet 1 at the speed inlet to 4m/s, and the gauge pressure of outlet 1 and outlet 2 at the pressure outlet to 0pa. Viscous Model is shown in Figure 10.

Design of diversion convex groove

In order to improve the wind speed at the exit, a diversion groove is designed on the swirl plate of the geometric model, as shown in Figure 11. The height of the bump is 10mm and the width is 40mm .



Viscous Model

Model
○ Inviscid
○ Laminar
○ Spalart-Allmaras (1 eqn)
○ k-epsilon (2 eqn)
● k-omega (2 eqn)
○ Transition k-kl-omega (3 eqn)
○ Transition SST (4 eqn)
○ Reynolds Stress (7 eqn)
○ Scale-Adaptive Simulation (SAS)
○ Detached Eddy Simulation (DES)
○ Large Eddy Simulation (LES)

k-omega Model
○ Standard
○ GEKO
○ BSL
● SST

k-omega Options
☐ Low-Re Corrections

Options
☑ Curvature Correction
☐ Corner Flow Correction
☐ Production Kato-Launder
☑ Production Limiter

Transition Options
Transition Model: none

Curvature Correction Options
CCURV: constant
1

Model Constants
Alpha*_inf: 1
Alpha_inf: 0. 52
Beta*_inf: 0. 09
a1: 0. 31
Beta_i (Inner): 0. 075
Beta_i (Outer): 0. 0828
TKE (Inner) Prandtl #: 1. 176
TKE (Outer) Prandtl #: 1
SDR (Inner) Prandtl #: 2
SDR (Outer) Prandtl #: 1. 168
Production Limiter Clip Factor: 10

User-Defined Functions
Turbulent Viscosity: none

Figure 10. Viscous Model

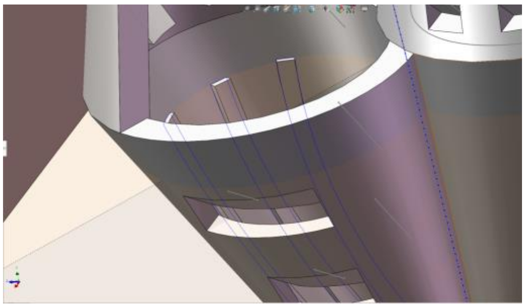


Figure 11. Convective Groove Design

RESULTS AND DISCUSSION

Solution results

After solving by Fluent, a point plane and a cross section are created at the bottom exit to obtain the wind speed results at the exit. By calculation, the velocity at the exit point is 3.66m/s. Figure 12 shows the velocity cloud diagram of the exit section. It can be seen from the figure that the wind speed of the single cavity outlet is close to 3.8m/s, indicating that the device has the effect of collecting wind.

The trace diagram of the wind collecting device after simulation is shown in Figures 13 and 14. By observing the trace track, it can be seen that under the interaction of natural wind pressure and pressure difference, the inner wall of the wind collecting device can form rotating wind to meet the design effect.

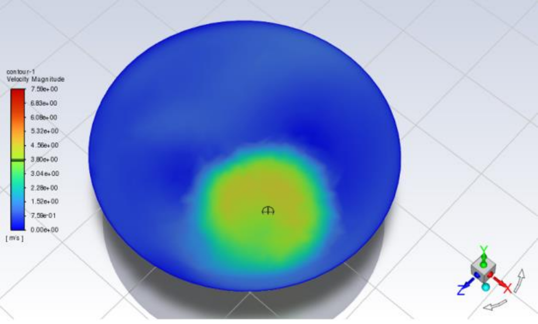


Figure 12. Cloud view of the exit section

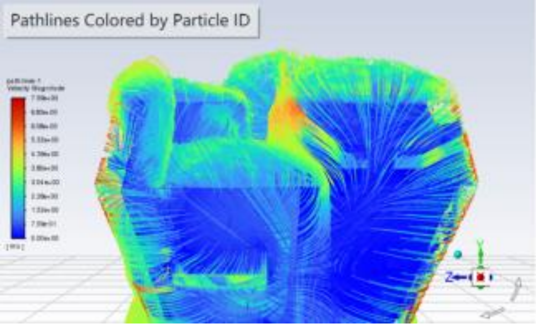


Figure 13. External Trace Diagram

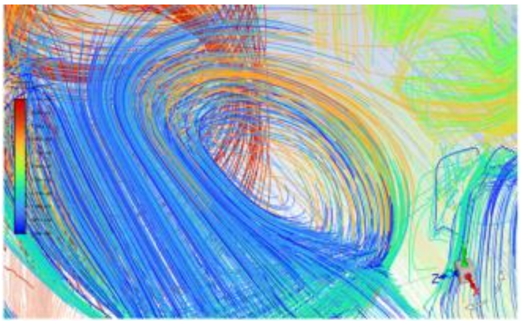


Figure 14. Internal Trace Diagram

Optimization design of wind collection device

Orthogonal optimization design

In this paper, the width and height of the diversion convex groove are taken as the design variable parameters, and the outlet wind speed is taken as the target parameter, which is optimized by orthogonal experimental design. Under the same conditions, the faster the outlet wind speed, the better the performance, representing the best parameters of the diversion convex groove.

According to the previous experiments, the width parameters of the diversion convex groove were selected as 40, 50, 60, 70, and the height parameters as 9, 10, 11, 12. Therefore, L16 (42) orthogonal table is selected. Using the simulation process shown above, the orthogonal table and simulation results are shown in Table 1. Using origin software to fit surface in Table 1, select poly33 as the fitting function to obtain the 3D diagram of the outlet wind velocity surface, as shown in Figure 15. It can be seen from the fitted surface results that when the width of the diversion convex groove is 47.35mm and the height is 10.65mm, the outlet wind speed is the highest, about 3.89m/s, so this parameter is the optimal value after orthogonal optimization design.

Table 1 Results of orthogonal design

Experiment Number	Width (mm)	Heigth (mm)	Outlet wind Velocity (m/s)
1	40	9	3.737074
2	40	10	3.758503
3	40	11	3.746586
4	40	12	3.730548
5	50	9	3.830914
6	50	10	3.849013
7	50	11	3.891313
8	50	12	3.876945
9	60	9	3.706883
10	60	10	3.713567
11	60	11	3.694844
12	60	12	3.677475
13	70	9	3.751493
14	70	10	3.792056
15	70	11	3.765875
16	70	12	3.730839

Physical experiment model

In order to verify the analysis results of the simulation software, physical models can be made and physical experiments carried out if conditions permit. The rationality and feasibility of the design scheme are confirmed by comparing the results of simulation experiment with those of physical experiment.

In this physical experiment, aluminum was selected as the material for making the model. Because the aluminum plate is easy to process, light weight and easy to assemble, it is suitable for equipment and structure with lightweight requirements.

According to the characteristics of the designed structure, the wind inlet plate and the swirl plate are connected by welding. In order to facilitate real-time adjustment during the experiment, the swirl plate and the wind inlet plate are connected by screws.

Figure 16 shows the overall physical experiment model, which has a compact structure in appearance. In order to verify the rationality of the wind collection of this

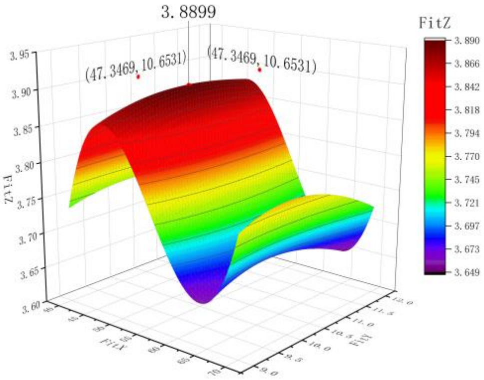


Figure 15. Surface Fitting Results

Figure 16. Overall Experimental Model

mechanical structure, a conventional horn fan in the market is adopted as the simulated wind source, with a power of 280W, a speed of 1400r/min and an experimental distance of 3m. In theory, the upper inlet plate structure can collect wind in all directions, and form rotating wind through the diversion convex groove inside the swirl plate for output. After many measurements, the experimental results are shown in Table 2.

It can be seen from the physical experiment that the wind collecting device can collect wind power, but there is a certain gap between the physical model and the simulation model. The possible reason is that the physical model is rough and cannot reach the ideal state of the simulation. However, the overall wind power trend of the device is the same, indicating that the wind power collection device has a certain feasibility.

Table 2 Measurement results of wind speed

Intake plate wind speed (m/s)	Wind speed of the collector (m/s)
4.0	2.8
4.0	2.8
4.0	2.9
4.8	3.6
4.8	3.9
4.8	3.8

CONCLUSION

The flow field analysis of the wind collecting device is one of the important links in the design of the device. In this study, the simulation model of the wind collecting device is designed and simplified, and the flow field characteristics are analyzed in fluent. The simulation results show that at a horizontal wind speed of 4m/s, the wind speed at the outlet is 3.66m/s, and rotating wind can be generated on the inner wall of this device. It means that the designed wind collecting device can meet the design requirements. In this paper, orthogonal design and surface fitting optimization are also carried out for the parameters of the simulation model. The result was that added a guide groove can increase the wind speed from 3.66m/s to 3.76m/s at the same wind speed. After optimization, the optimal values for the width and height of the guide groove are 47.35mm in width and 10.65mm in height. At this point, the wind speed at the outlet increases to 3.89m/s. Finally, in order to verify the analysis results of the simulation, physical experiments were conducted to verify the wind collection device, confirming that the simulation results are consistent with the physical results. Due to the idealized simulation model, there was a certain gap between the simulation results and the physical experimental results. Further optimization of the simulation model and physical model was required. The current design of the air collection device still had some imperfections, such as the angle of the air inlet plate, the opening position of the movable plate, and other parameters that can be optimized. In the future, the height, shape, and material of this device can be designed and optimized to adapt to different environmental and economic conditions.

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CONFLICT OF INTEREST

The authors confirm that there is no conflict of interest in this research.

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Persian Abstract

چکیده

در این مقاله، نوع جدیدی از دستگاه جمع‌آوری باد که می‌تواند باد دوار برای تولید برق بادی تولید کند، برای رفع کاستی‌های دستگاه‌های تولید برق فعلی بادی طراحی شده است. این دستگاه می تواند با تغییر جهت باد انرژی باد را از جهات مختلف جمع آوری کند. ابتدا مدل شبیه سازی این دستگاه جمع آوری باد توسط نرم افزار SolidWorks طراحی شده است. در مرحله دوم، میدان جریان داخلی مدل با استفاده از دینامیک سیالات محاسباتی مدل‌سازی و شبیه‌سازی شد و مدل k-ω SST در فلوئنت برای تحلیل میدان جریان انتخاب شد. نتایج نشان داد که این دستگاه می تواند سرعت باد خروجی ۳/۸ متر بر ثانیه را با سرعت باد ۴ متر بر ثانیه ایجاد کند که اثر جمع آوری باد دستگاه را تأیید می کند. ثالثاً سرعت باد خروجی به عنوان هدف بهینه سازی در نظر گرفته شد و طراحی بهینه سازی متعامد بر روی شیار محدب راهنما در مدل انجام شد و پارامترهای طراحی بهینه شیار محدب راهنما تعیین شد. نتایج نشان داد که وقتی عرض شیار محدب انحرافی ۴۷/۳۵ میلی‌متر و ارتفاع آن ۱۰/۶۵ میلی‌متر باشد، سرعت باد خروجی در حدود ۳/۸۹ متر بر ثانیه است. در نهایت برای تأیید نتایج تحلیل شبیه‌سازی عددی، تأیید تجربی دستگاه جمع‌آوری باد از طریق نمونه‌های اولیه فیزیکی انجام شد. نتایج نشان داد که نتایج شبیه‌سازی با نتایج فیزیکی مطابقت دارد. طراحی این دستگاه می‌تواند پشتیبانی نظری را برای طراحی بعدی یک دستگاه جمع‌آوری باد تمام جهت برای مقابله با شرایط پیچیده جهت باد فراهم کند.