Design for the turbine of solar chimney power plant system with vertical collector

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Abstract. Based on the design theory of the wind turbine, a turbine applied to solar chimney power plant with a vertical collector is designed, and the performance of the wind turbine is conducted by wind tunnel test. The results point out that the experimental performance is consistent with the designed performance. Then the number of blades and tip speed ratio are conducted, as well as we obtained the optimum blade number and tip speed ratio of turbine for the system.

1. Introduction

The solar chimney power plant system, which was first put forward by Professor Schlaich in 1978, can convert solar radiation into electrical energy without generating pollution[1~3]. Many scholars have carried out a lot of research on the operation characteristics, flow field, energy conversion process, and the structure of power plant system, which proved that the solar chimney power generation system has the advantages of low power generation technology, operation and maintenance[3]. However, due to its large area and high chimney, the application of it is limited. Qing-Ling Li [4] combined the solar power generation technology with the building and designed a kind of vertical solar chimney power plant system applied in the urban area, as shown in figure 1. In this new kind of solar chimney power plant system, the vertical solar chimney is made from transparent materials supplemented with the enclosed air absorbing solar energy and flowing upward[4]. At the same time, the external cold air enters into system constantly, thereby forming an air circulation. The turbine driving a generator is installed at the bottom of the chimney, where the differential pressure is greatest, so that the energy of the air pressure difference can be used best.

For the solar chimney power plant system with vertical heat collector, Yan Zhou [4~8] introduced its structure and the principle of power generation. A mathematical model considering the influence of size, solar radiation, and environmental conditions have been made; A new type of heat collector and accumulation device has been designed, and the shape of the flow channel has been optimized; And the relationship between system power and the height, width, and thickness of the air layer of the heat collector has been analyzed. However in the power station system, the main equipment that converts the of other forms of energy into mechanical energy is the turbine. The performance of the which is also directly affect the improvement of the system energy conversion process.

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The design of turbine in solar chimney power plant system with vertical heat collector began in a paper devoted to the study of the characteristics of a solar chimney power plant published by Backstrm and Gannon. In this paper, the theoretical analysis method was used to explain the influence of turbine fluid flow and load coefficient on the efficiency of turbine\cite{9}. F. Denantes and E. Bilgen developed an efficient model of counter-rotating turbines for a solar chimney\cite{10}. The air flow condition of 200MW solar chimney power plant was calculated and the turbine was designed by Puprecht. Ting-Zhen MING et al. designed and analysed the heat collector, wind turbine, and conducted the influence of each parameter on the system \cite{11}.

![Figure 1. The chart of solar chimney power plant system with vertical heat collector.](image)

Although the temperature field of the solar chimney is similar to that of the traditional solar chimney power plant, the speed gradient of the system is obviously larger, and the pressure gradient is less\cite{12}. Therefore, as far as the solar chimney power plant system with vertical heat collector, the main energy of hot air flow in the system is kinetic energy, the static pressure energy and heat energy is relatively small. According to the characteristics of energy in the system, this paper intends to design a turbine applied to solar chimney power plant system with vertical heat collector based on the design principle of the wind turbine, and make a detailed study of the performance.

Blade is the base and key components for the wind turbine, it directly affects the performance and cost of the whole machine. Wind turbine blade design is divided into aerodynamic shape design and structural design, the main task of aerodynamic shape design is to choose appropriate airfoil and calculate the chord length of the blade and installation angle to determine the external surface of the blade. At present, the design of the turbine blade design theory is a lot, the more famous of which have Schimitz theory, Clauert theory and Wilson theory; Because Wilson theory makes the improvement of Glauert theory, analyzes the tip loss and lift drag ratio on the optimum performance of the blade. Therefore, the theory is widely used in blade aerodynamic performance calculation. Based on the design theory of the wind turbine, this paper uses Matlab software to solve the geometric parameters of wind turbine blade profile and the physical model of the turbine is established by using SolidWorks software, then and the performance of the wind turbine is investigated by wind tunnel test.

2. Calculation of turbine design

2.1. General parameters of turbine design

In the solar chimney power plant system with vertical heat collector, the main parameters of turbine blade design include: impeller diameter, blade number, blade airfoil, the airfoil chord length and
installation angle. According to the data provided by the literature [13~14], the average wind speed of the system is $V = 5\text{m/s}$. In the design calculation, the wind energy utilization coefficient is set as $C_p = 0.35$, wind turbine electrical and mechanical efficiency $\eta_1 \cdot \eta_2 = 0.9$. As the flow channel diameter of the experimental power station is $0.45\text{m}$, it can be assumed that the diameter of the wind wheel is $D = 0.43\text{m}$.

2.2. Determination of turbine power

The power of the turbine equipment of the experimental power station can be calculated according to the calculation formula provided by the literature [14]:

$$P = 0.5 \rho V^3 AC_\pi \eta_1 \eta_2$$  \hspace{1cm} (1)

$\rho$ is air density, its value varies with the change of air temperature. In the solar chimney power plant system with vertical heat collector, turbine is placed in the top of the collector. The simulation results point out that the air temperature increases with the increase of the height of the heat collecting plate. That is, the temperature at the top of the collector is lowest, so assuming that the temperature is $30^\circ\text{C}$, and the air density is $1.169 \text{kg/m}^3$. $A$ is swept area of the wind wheel. The power of the turbine can be calculated: $P = 2.45W$.

2.3. Determine the number of blades, tip speed ratio and airfoil

There is a certain relationship between the number of blades and the power of turbine. In general, under the conditions of low flow rate, multiple-blade has high efficiency and start-up characteristics. 6 blade turbine with wonderful balance refuse to produce disturbance to the turbine. Therefore, the number of blades are determined to be 6; At the same time according to the relationship of tip speed ratio and the number of blades, tip speed ratio is assumed to be 3.

The performance of the airfoil directly affects the efficiency of the overall generator. The aerodynamic performance of the blade, the quality of the blade and the difficulty of manufacturing are comprehensively considered when the airfoil is selected. Excellent airfoil should possess a larger lift coefficient and a smaller drag coefficient, which makes the lift drag ratio tend to reach the maximum. NACA63-215 airfoil is commonly used in the traditional wind turbine airfoil. At different angles of attack, it has a different lift drag ratio. When angle of attack is 7 degrees with the maximum lift drag ratio of 14, the airfoil lift coefficient is $C_l = 0.7$, drag coefficient is $C_d = 0.05$ [15].

2.4. Blade design model

Based on the Wilson approach to establish the design procedure of the blade, the design method of high precision will obtain chord length and installation angle of each leaf element.

2.4.1. Objective function

When the partial loss of the blade is considered, the local optimum power coefficient of the blade $dC_{p\pi}$ can be determined:

$$\frac{dC_{p\pi}}{d\lambda} = -\frac{8}{\lambda^2} b(1-a)F \lambda^3$$  \hspace{1cm} (2)

Where: $b$ is circumferential induction factor; $a$ is axial induction factor; $F$ is loss coefficient; $\lambda$ is tip speed ratio at $r$ of wind wheel radius. According to equation (2) the power factor of the whole blade reach the maximum value, it is necessary to make the maximum value of $\frac{dC_{p\pi}}{d\lambda}$ from each leaf blade surface.
2.4.2. **Constraint condition**

In order to determine the maximum value of the objective function in the formula (2), the constraint conditions must be satisfied:

\[ b(1 + b)\lambda^2 = a(1 - aF) \] (3)

Iterative computation of each leaf element a, b, F, and F by the formula (4), (5), (6) to determine:

\[ F_{\text{tip}} = \frac{2}{\pi} \cos^{-1} e^{-\frac{b R - r}{2 r \sin I}} \] (4)

\[ F_{\text{hub}} = \frac{2}{\pi} \cos^{-1} e^{-\frac{b r - R_{\text{hub}}}{2 r \sin I}} \] (5)

\[ F = F_{\text{tip}} \cdot F_{\text{hub}} \] (6)

Where: \( F_{\text{tip}} \) is tip correction factor; \( F_{\text{hub}} \) is leaf root correction factor; \( R \) is impeller radius, m; \( r \) is blade element section to the center of the wind wheel, m; \( I \) is flow angle of leaf element (°).

The calculation formula for blade chord:

\[ BcC_{l} = \frac{8\pi a F(1 - aF) \sin^2 I}{(1 - a)^2 \cos I} \] (7)

The calculation formula for the installation angle of the blade is:

\[ \tan I = \frac{(1 - a)V}{(1 + b)w r} = \frac{(1 - a)}{(1 + b)\lambda} \] (8)

\[ \beta = I - \alpha \] (9)

Where: \( \beta \) is Blade mounting angle, (°). \( c \) is blade chord length, m.

### 2.5. Wilson optimization design steps

| Radius \( r \) (m) | Axial induction factor \( a \) | Circumferential induction factor \( b \) | Inflow angle \( I \) (°) | Chord \( L \) (m) | Installation angle \( \beta \) (°) | Loss coefficient \( F \) |
|-----------------|------------------|------------------|------------------|-----------------|------------------|------------------|
| 0.05            | 0.3303           | 0.3202           | 34.0902          | 0.0559          | 27.0902          | 0.8481           |
| 0.065           | 0.3229           | 0.1969           | 30.1383          | 0.054           | 23.1383          | 0.9479           |
| 0.08            | 0.3253           | 0.1362           | 26.3419          | 0.0506          | 19.3419          | 0.9675           |
| 0.095           | 0.3273           | 0.0998           | 23.2424          | 0.0468          | 16.2424          | 0.9757           |
| 0.11            | 0.3293           | 0.0762           | 20.7022          | 0.0431          | 13.7022          | 0.9768           |
| 0.125           | 0.3315           | 0.0603           | 18.5955          | 0.0397          | 11.5955          | 0.9727           |
| 0.14            | 0.3345           | 0.049            | 16.8182          | 0.0368          | 9.8182           | 0.9619           |
| 0.155           | 0.3391           | 0.0411           | 15.2793          | 0.0342          | 8.2793           | 0.9381           |
| 0.17            | 0.3488           | 0.0358           | 13.8569          | 0.0321          | 6.8569           | 0.884            |
| 0.185           | 0.3734           | 0.0339           | 12.3261          | 0.0307          | 5.3261           | 0.7445           |
| 0.2             | 0.3869           | 0.0309           | 11.793           | 0.0306          | 4.793            | 0.6703           |

(1) Blades will be divided into equal parts along the radial direction of blade, the first airfoil with radius \( r = 0.05 \) m, \( r = 0.015 \) m for every part.
(2) For a per leaf element, with formula (2) as the objective function, type (3) and (6) as the constraint condition and objective function for solving the optimization function, we can acquire inducing factor a, b and the correction factor F.

(3) According to the formula (8), the installation angle of each section is solved.

(4) Equation (7) can be used to solve the chord length C.

In the design of blade process, Matlab programming tool plays a very important role. In the choice of optimization function, we select the fmincon function, and nonlinear multi constraint problem is usually solved with this function, thus the accuracy is higher.

The aerodynamic shape of the blade is obtained as shown in table 1.

3. 3D solid modeling of blade
According to the coordinate geometry transformation principle, the 3D coordinates of each section in the space are solved. The 3D space coordinate is saved as the notepad file, and the SolidWorks software is directly introduced into the model to extract the diagram of each blade airfoil section and The 3D solid model of blade, that are shown in figure 2 and figure 3.

4. Experimental study on turbine performance

4.1. Experiment principle
The low speed wind tunnel used in this experiment is shown in figure 4. The experimental section is a cylindrical pipe, the ratio of which to the actual channel is 1:1, and the turbine is made according to the actual design size.
Figure 5 is the experimental principle diagram, the turbine connects with the generator directly using coupling. The generator carries on the load, so as to measure the current and voltage of the generator exporting, and deduce the turbine power. Therefore turbine's performance can be comprehensively analysed. In the system of wind tunnel, the air enters the passage from the left side of the nozzle as shown in the diagram, and after contraction section, its speed greatly improves, then it enters the experiment section of the system.

Turbine blades are made by 3D printing technology. The blade model is shown in figure 6. Rotating speed is measured by speed measure module that includes a STM32 development board and photoelectric rotary encoder. We use the standard GM8901 handheld wind speed meter to measure the air speed of the experiment section. The position of the pressure measure point is shown as figure 6, and we use the differential pressure gauge to measure the differential pressure.

4.2. Experimental results
Figure 7 and figure 8 are relationship between power and wind speed and differential pressure. We can observe that the power of turbine increase with turbine inlet speed and pressure difference increases. The greater the inlet speed and pressure difference, the greater the output power of the turbine. And it is observed that the turbine power changes in accordance with the exponential relationship with the variation of the wind speed at the turbine inlet, and changes in accordance with the linear relationship with the variation of between and after the turbine, which indicates that the turbine can utilize the air energy better than the pressure energy.

We can also find that the starting wind speed of the 6 blade turbine is about 4m/s. But in the experiment we notice that after the turbine starts rotating, even when the wind speed is less than 4m, turbines will not immediately stop rotating. Through testing, when the wind speed reduces to 3m/s, turbine will stops rotating. The difference in speed between of them is about 1m/s. The experimental data obtained are referred to in figure 9.

4.3. Comparative analysis of designed and experimental values of blade performance

Figures 10 and 11, respectively point out that relationship between designed and experimental power and inlet speed and differential pressure. As can be observed from the figure, the designed values and experimental values are similar, and there is the same trend. There are some differences between
experimental and design values, and the greater the wind speed are, the greater the difference is. There may be some reasons for the error, on the one hand, in the design of the blades, the wind energy utilization coefficient, tip speed ratio and other parameters are assumed to be an approximation according to experience. On the other hand, measuring and reading test dates have unavoidable errors in the experiment.

5. Optimization of turbine

5.1. Optimization of blade number

In order to obtain the optimum blade number of the turbine for vertical solar chimney power plant, the turbine of the other number of blades must be tested. Since wind speed of this system is relatively small, in order to extract a small starting wind speed, so we try to use multi-blade turbine. Due to the limited size of the hub, when the number of blades reaches 9, the hub can not meet the size requirements of the number. Therefore, the redesigned turbines with blade number of 5, 7, 8 are conducted. Understood by the design of the blades, we can know the greater the number of blades, the blade smaller the width of the blade. The experimental dates are shown in figure 12.

As can be observed from the figure 12, the power of the turbine with different number of blades is slightly different, especially at low wind speed. When the wind speed is increased, we can observe that the number of 6 blades of turbine power is the highest, followed by 5 blades, 8 blades of turbine power is minimum. As far as starting wind speed, it can be concluded that the number of minimum starting wind speed is 8, whose value is 3.5m/s. The starting wind speed of 5 blade turbine is the highest, whose value is 4.2m/s. Therefore, taking into account the cost, power, starting wind speed and other factors, we selected the optimum number of the turbine blades is 6.

5.2. Optimization of tip speed ratio

In the above design, the tip speed ratio is assumed to be 3. When the wind speed is constant, change the tip speed ratio amounts to alter the rotating speed. Therefore, when the wind speed is 5m/s, the rotating speed of the turbine in the off-design condition is changed to acquire the best tip speed ratio.

Figure 13 is the relationship between turbine power and tip speed ratio. We can conclude that the power of the turbine increases firstly and then decreases with the increase of the tip speed ratio. The turbine has the maximum power when the tip speed ratio is 1.9.
Therefore, the turbine has the optimum blade number and tip speed ratio. This is because when the number of blades and tip speed ratio is large, it will block the wind passing through the turbine, thereby reducing the power of the turbine.

6. Conclusion
Based on the design theory of the wind turbine, a turbine applied to solar chimney power plant with a vertical collector is designed, as well as the performance of the turbine is analyzed by experiments. The following conclusions are obtained:

- Based on the Matlab platform, we adapt Wilson design theory to solve parameters of each blade airfoil section. At the same time, the NACA63-215 airfoil is chosen as the airfoil of the blade design. Finally, the physical model was built with Solidworks software.
- The performance of the wind turbine is conducted by wind tunnel test, which is compared with the design power. The results refer to the experimental power is consistent with the design power.
- Through the experimental method, we come to conclusion the optimum blade number is 6, the optimum tip speed ratio is 1.9.

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