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An analysis of the impacts of the number and angle of miniature wind turbine blades on the efficiency----Based on modern horizontal-axis wind turbines

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Abstract:

As the energy crisis becomes much more serious, renewable energy is needed as a solution. Among all the renewable powers, wind power plays a significant role. Although there has been much research on modern wind turbines, almost no studies focus on miniature wind turbines. To fill the research gap, here the author applies both literature research and control-variable experiments to take a deeper insight into how the number and angle of miniature wind turbine blades affect the efficiency and whether there are some differences in the impacts of the two factors on the efficiency between miniature wind turbines and modern wind turbines. It is found out that as the number of blades increases from 1 to 4, the efficiency would grow while there's a slight decrease when the blade number becomes 5. Moreover, the four-bladed miniature wind turbine with 0 degrees is figured out to be the better design without consideration of cost compared with modern wind turbines. The rate of growth also shows a great difference between modern and miniature wind turbines. The gradient increases as the number of blades rises for miniature wind turbines, and that of modern wind turbines has the opposite trend. This study has shed light on the area of miniature wind turbines. And it's innovative to research the angle between structural lines in the modeling process.

Keywords: miniature wind turbines, blade number, blade angle, efficiency, modern wind turbines

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1. Introduction

In recent years, it has become increasingly difficult to ignore the energy crisis. Mackay (2009) had already pointed out the main motivations behind this: 'First, fossil fuels are a finite resource. Second, we're interested in security of energy supply. Third, it's very probable that using fossil fuels changes the climate'(p.5). Unfortunately, the Energy Information Administration (EIA) projected that world energy consumption will grow by nearly 50% between 2018 and 2050, which means there's a dramatic increase in energy demand that may lead to a more serious crisis (Kahan, 2020). Therefore, one of the most essential current discussions is renewable energy. Renewable energy-including solar, wind, and hydroelectric power-is predicted to be the fastest-growing energy source currently, surpassing petroleum and other liquids to become the most used energy source (Kahan, 2020).

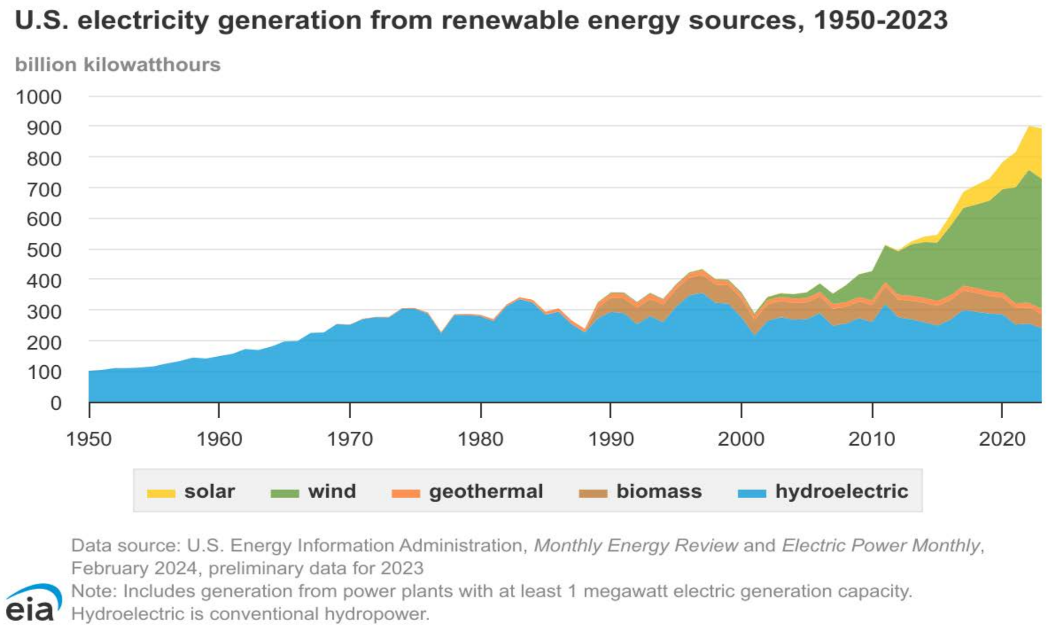

Figure 1 U.S. electricity generation from renewable energy sources, 1950-2023

(U.S. Energy Information Administration, 2024:p.1).

According to Figure 1, wind has become one of the major renewable energy sources, generating 425.00 billion kilowatt-hours of electricity in the U.S. in 2023 (U.S. Energy Information Administration, 2024). Wind turbines convert the wind's kinetic energy into mechanical energy to produce electricity (Sudarma et al., 2020). And it's of great significance to emphasize that 'a wind turbine blade is an important component of a clean energy system because of its ability to capture energy from the wind' (Adeyeye, Ijumba & Colton, 2021:p.1). As a result, there have already been a great number of studies about the factors of wind turbine blades. However, almost no researchers take a look at those miniature wind turbines which may have different properties from these modern wind turbines. The miniature wind turbine mentioned represents the miniature wind turbine model sold online (Figure 2).

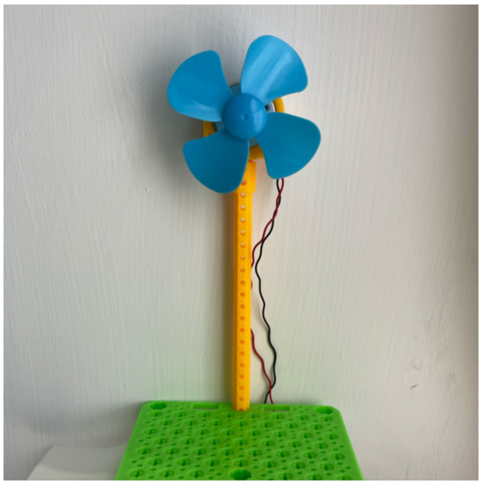

Figure 2 A Miniature Wind Turbine

The purpose of this paper is to explore how the number and angle of miniature wind turbine blades affect their efficiency based on the existing research on modern horizontal-axis wind turbines. Also, the research will figure out whether there is a difference in the impacts on the efficiency between miniature wind turbines and modern horizontal-axis wind turbines. In this study, objective literature research and control-variable experiments will be applied. For the literature research, the history, the developing trend of wind turbines, the essential physical knowledge, and the impacts of the number and angle of modern wind turbine blades on efficiency are collected as secondary research. Moreover, the experiments are carried out to test the effect of miniature wind turbine blades' number and angle on efficiency as the primary research. One-bladed, two-bladed, three-bladed, four-bladed, and five-bladed miniature wind turbine blades with distinct angles (0 degrees, 30 degrees, and 60 degrees) will be tested to get scientific data. The data will be analyzed from different aspects to get a sufficient result.

2. Literature review

The research aims to explore the impacts of the number and angle of miniature wind turbine blades on the efficiency, based on modern horizontal-axis wind turbines. The history and developing trend of wind turbines offer a primary understanding of the area and clearly show that it's reasonable to choose modern horizontal-axis wind turbines as the research foundation due to their high efficiency. Meanwhile, the introduction of power coefficient, Cp, and Betz limit is essential, laying a solid foundation for having a deeper insight into the following content. In addition, the review will mainly focus on the comparison between the methods and the results with the consideration of other factors like the drag effect.

2.1 History of wind power & wind turbines

The previous papers provide a sufficient overview of the history and developing trend of wind power and wind turbines.

2.1.1 Wind Power

Wind power has been recognized and applied in human life since antiquity. It is concluded that 'for thousands of years, wind energy has been employed to sail boats, pump water, grind grain, saw timber, shred tobacco, and press oil,' telling the wind application in the past (Möllerström, 2024: p.1). There are mainly four types of wind power utilizations: Firstly, people have used wind energy to lift water since the second half of the twentieth century, which has figured out the irrigation and drinking water problems. The second is sails-aided navigation, contributing to fuel saving, followed by wind heating which has made a great contribution to the high-altitude regions. And wind power generation is becoming the major way of wind utilization all over the world in today's society (Caiet al., 2014).

2.1.2 Wind Turbines

Wind turbines have experienced a long-term development until now.Beurskens (2014) divided the period into four sections: Classical period where classic windmills were mechanical, started in 600 and ended after the discovery of the steam engine. The development of electricity-generating wind turbines (1890-1930) existed, followed by the first phase of innovation (1930-1960) as the Second World War stimulated new innovations. The last phase began in 1973 with a second period of innovation and mass production due to the energy crisis and environmental problems. The brief division helps to find a basic understanding of the developing periods while Hau (2013)provided a clear comparison graph of the efficiencies of the wind turbines on the developing trend, Figure 3, presenting the superiority of three-bladed horizontal-axis wind turbines (Hau, 2013:p.105).The three-bladed horizontal-axis wind turbine is representative enough that it is closest to the highest efficiency--the Betz Limit (59.3%), explaining the reason for choosing it as the foundation of the research.

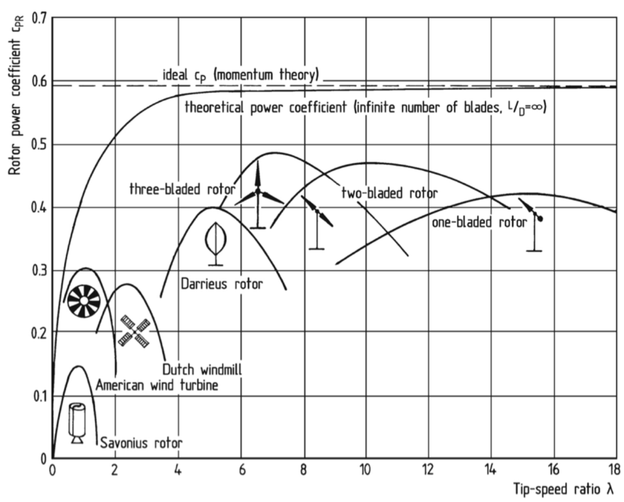

Figure 3 Power coefficients of wind rotors of different designs (Hau, 2013:p.105)

In conclusion, the rapid development of wind utilization took place in the past periods, leading to the wide use of wind turbines nowadays.

2.2 The Power Coefficient (Cp) and Betz Limit

'The power coefficient is defined as the ratio of the power extracted by the wind turbine relative to the energy available in the wind stream', representing the efficiency of a wind turbine (Ragheb, 2011:p.32). A higher power coefficient means that the wind turbine can more effectively convert wind energy into power output. And a formula can just be obtained from the definition:

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$$C_p = \frac{P_t}{P}$$

To make it easier to understand, the kinetic energy of an air mass m moving at a velocity v can be expressed as (Hau, 2013):

$$E_k = \frac{1}{2}mv^2$$

As the density is ρ, the mass is:

$$m = \rho V$$

where V is the volume, which could be written as:

$$V = SL = Svt$$

The equations could be used together to express the kinetic energy of the air flowing through the wind turbine with cross-sectional area S, in terms of the blade radius r (Ragheb & Ragheb, 2011):

$$E_k = \frac{1}{2}\rho v^3 St = \frac{1}{2}\rho v^3 \pi r^2 t$$

From the equation,

$$P = \frac{E}{t}$$

the total power is expressed as:

$$P = \frac{1}{2}\rho v^3 \pi r^2$$

leading to the specific expression of power coefficient:

$$C_p = \frac{P_t}{\frac{1}{2}\rho \pi r^2 v^3}$$

After complex formula derivations, Betz found the theoretical maximum efficiency wind turbines can achieve which is the Betz limit, 59.3%. Adeyeye, Ijumba, and Colton (2021) state that ‘Designers of most commercial wind turbines, which are mostly horizontal axis wind turbines and a few vertical axis wind turbines, have tried to design wind turbines that operate at efficiencies close to the Betz limit,’ showing the importance of the coefficient (p.1).

To conclude, the power coefficient is an important indicator showing the efficiency of a wind turbine, and the Betz limit is the maximum power coefficient wind turbines could achieve theoretically.

2.3 The effects of the blade number and angle on the efficiency

The existing studies about the topic have drawn different conclusions by using different methodologies. In early times, Wilson, Lissaman, and Walker (1976) believed as the blade number grows, the power coefficient, Cp, will also increase and become closer to the Betz limit. However, the preconditions for the result are too ideal, which means the loss of energy due to drag effects and other factors is neglected. The situation is impractical in the real world.

In contrast, research carried out with the stimulation of Computational Fluid Dynamic (CFD) has gained a totally contradictory result that from 2 blades to 4 blades, ‘power coefficient actually decreases as the number of blades increases’(Newbauer & Kumpaty, 2012:p.1). The researcher took the blade interactions and drag effects into account to analyse the model, coming to the conclusion that the decrease in Cp is the result of increasing drag effects (Newbauer & Kumpaty, 2012). Compared with the current situation, it seems to be contrary to the use of three-bladed wind turbines instead of two-bladed wind turbines. The CFD method is also applied in another study, together with experiments to compare the computational data and the experimental results, which makes the research findings more accurate and comprehensive. Blade numbers of 2, 3, 5, and 6 were tested in the process:

‘It is found that decreasing the number of blades ... the wind turbine with 3 blade configuration has the maximum power coefficient in respect to 5 and 6 blade turbines, higher by around 2 and 4 percent respectively.’(Eltayesh et al., 2021:p.1)

The conclusion given is in accord with the situation that many wind turbines these days are three-bladed. As reported by Sudarma et al. (2020), by simulating turbines in various wind velocities with blade number variation of 3, 4, and 5 blades in ANSYS Fluent and experimenting with a 5-bladed wind turbine model, the researchers came up with an accumulative result: the generator efficiency in reality was lower than the predicted one because more unidentified energy losses existed and were not accounted for. The opinion mentioned points out the drawbacks of using the method. Moreover, it now seems clearer that the decreasing results of Cp in the other research using the combination of methods may be due to the overestimation of the drag effects and interactions between blades.

Therefore, the experimental studies are relatively closer to reality. According to NEI et al. (2015), the research, which is carried out by testing wind turbines with different blade numbers from 2 to 4 and the same tilt angle of 60 degrees, showed that the four-bladed wind turbine is the one that could reach the highest power output in the specific condition: tile angle 60 degrees, wind speed 8 m/s. Nevertheless, the experiment is a bit monotonous as the tilt angle always remained at 60 degrees in the sets of experiments.

For the previous studies in wind turbine angles, CFD simulation is widely used. Research has used NACA 4412 profile as the model foundation, carefully including the simulation pictures in ANSYS Fluent and a table to show the maximum generated power at distinct blade angles

(Abuzaid et al., 2017). The authors come to the conclusion that 'for blade angle change from 20° to 60°, the wind power has a small increase and reaches the maximum when blade angle equals to 90°'(Abuzaid et al., 2017). In another research, horizontal wind turbines modelled with the blade foundation NACA 4420 experienced CFD analysis and the results were compared with those values in the wind tunnel experiments, telling that the simulation data is proved by the experiment (Chandrala, Choubey & Gupta, 2012). The specific result related to the power and angle of the blade is almost the same as the mentioned one. Another study presents that as the angle of attack increases, the drag coefficient grows while the lift coefficient rises until 40 degrees and then drops, showing the performance might be weak when the angle of attack is too high(Patil & Thakare, 2015).

The existing studies focus more on how the number and angle of modern wind turbine blades affect the efficiency. However, there are few studies taking a deeper insight into those miniature wind turbines. Therefore, this study intends to show how the number and angle of miniature wind turbine blades affect efficiency.

3. Methodology

3.1 Overview

This dissertation is carried out with a combination of primary and secondary research. Firstly, for secondary research, sufficient literature research is conducted on the background information, essential theoretical knowledge, and the existing materials on the research topic. Secondly, the author also adopts the primary research. Control-variable experiments are applied to test miniature wind turbine blades with different blade numbers and angles to figure out the better miniature wind turbine blade and compare the impacts of the two factors on efficiency between miniature wind turbines and modern horizontal-axis wind turbines.

3.2 Literature research

In terms of literature research, the research has collected information on the current energy crisis, the history, developing trends of wind turbines, physical knowledge including the Betz limit and power coefficient, and the existing materials on how the number and angle of wind turbine blades affect efficiency. This information is used to introduce the popularity of wind power, give a primary understanding of the area, lay a solid theoretical foundation for the following content, and present the research status to point out the research gap and compare the results. Those materials are published from 1976 to 2024. All the resources mentioned are mainly from professional platforms like CNKI, Google Scholar, and credible websites such as the U.S. Energy Information Administration. Also, as the contents are selected by the author using the CRAAP principle, the currency, relevance, authority, accuracy, and purpose of the materials have been well assessed.

3.3 Experiment design

3.3.1 Experimental Objects

For the experimental objects, at different angles (0°, 30°, and 60°), there are blade numbers ranging from 1 to 5.

All the experimental objects are initially modeled by the author using SolidWorks and then printed. The modelling process could be divided into three sections:

In the beginning, as the experimental objects are based on the miniature wind turbine blades sold online and almost no drawings with accurate data are available, the author measures the sample blade (Figure 4) with a vernier caliper and sketches a primary drawing of it.

Figure 4 The sample blade

After the measurement process, the revolved modeling method is used to build the hub for all the blades. The exact values of the hub are shown in Figure 5.

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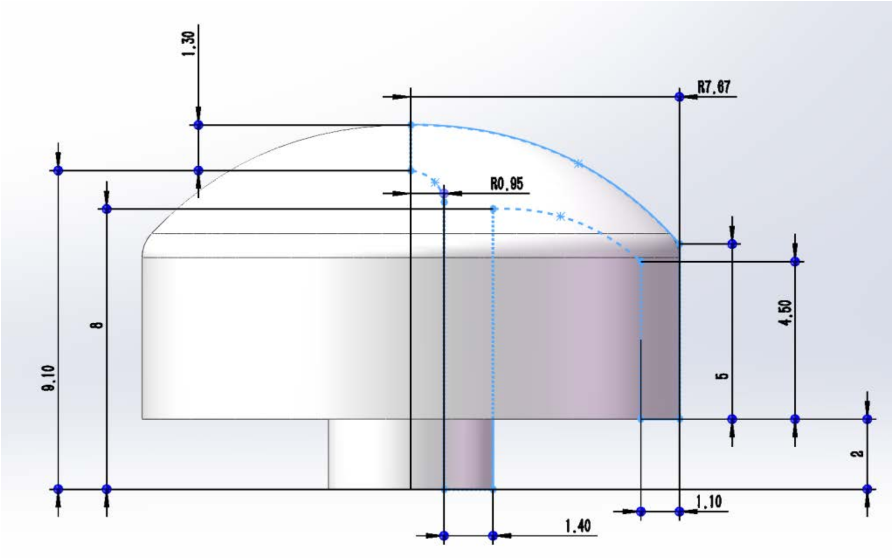

Figure 5 The model of the hub

When it comes to the blades, the author constructs two structural lines with an included angle on distinct datum planes to make the blades by means of surface lofting. It's of great importance to emphasize that the angle between the two structural lines is the angle discussed in this study. Figure 6, Figure 7, and Figure 8 illustrate the blade angles from 0 degrees to 60 degrees. Then, experimental subjects with various blade numbers are established by circular pattern in SolidWorks.

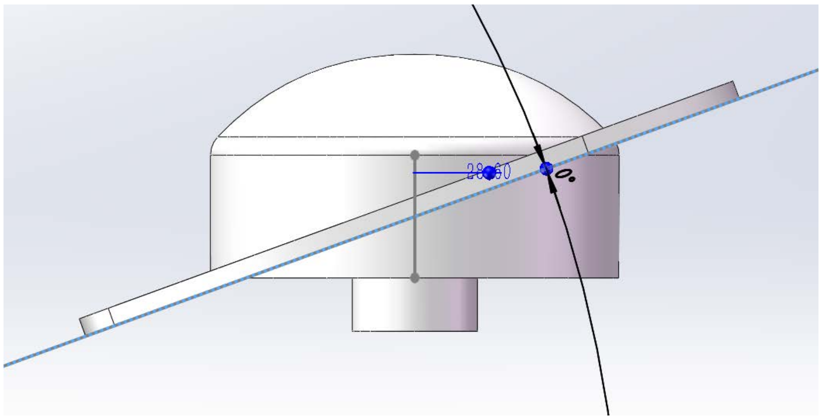

Figure 6 0 degrees one-bladed

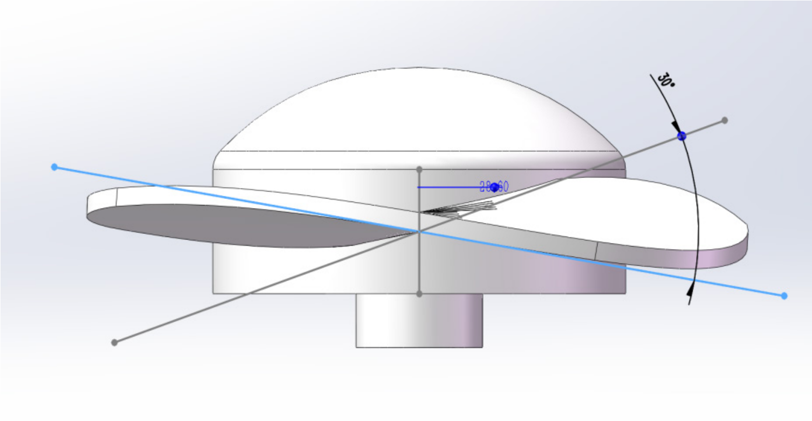

Figure 7 30 degrees one-bladed

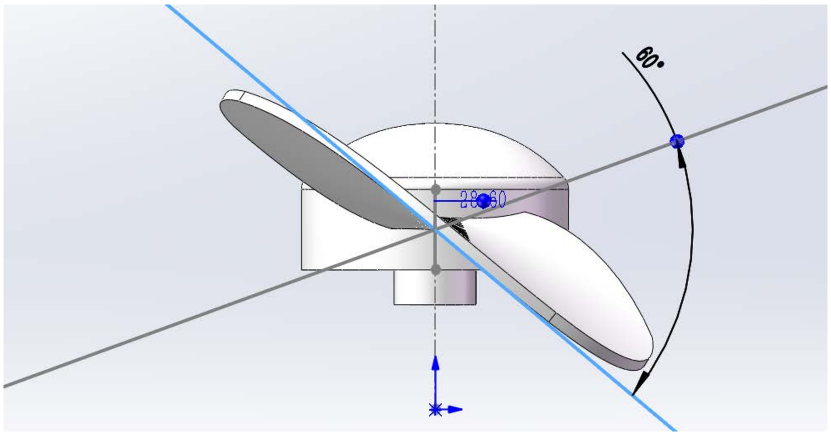

Figure 8 60 degrees one-bladed

Figure 9 shows all the models printed for the experiments. Each of the blade models is printed twice for backup.

Figure 9 The models printed

3.3.2 Data and Information Needed

From the formula of power coefficient, Cp:

$$C_p = \frac{P_t}{\frac{1}{2}\rho\pi r^2 v^3}$$

The density ρ is set to be the air density, which is 1.225 kg/m^3, while the radius of the blades has already been figured out during the modeling process, which is 0.0286 m.

What remained to be measured directly in the experiments was the current and voltage, contributing to the calculation of power generated. Also, the wind velocity is measured once and assumed to be constant at 7.6 m/s because the batteries for generating wind are assumed to have almost no loss of charge during the short experimental process. Table 1shows the data which needs to be recorded in the author's experiments.

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Table 1 The impacts of the number and angle of miniature wind turbine blades on efficiency

Angle(°) / Number	0				30				60			
		Current (mA)	Voltage (mV)	C_p		Current (mA)	Voltage (mV)	C_p		Current (mA)	Voltage (mV)	C_p
1	1				1				1			
	2				2				2			
	3				3				3			
	AVG				AVG				AVG			
2	1				1				1			
	2				2				2			
	3				3				3			
	AVG				AVG				AVG			
3	1				1				1			
	2				2				2			
	3				3				3			
	AVG				AVG				AVG			
4	1				1				1			
	2				2				2			
	3				3				3			
	AVG				AVG				AVG			
5	1				1				1			
	2				2				2			
	3				3				3			
	AVG				AVG				AVG			

3.3.3 Experimental Instruments

In the measurement section, the vernier caliper used is a digital display simple caliper with a measuring range of 0-150 millimeters and a resolution of 0.1 mm (Figure 10).

Figure 10 The digital display simple caliper

The instruments for the experiments, including two multimeters, an anemometer, a 10-ohm resistance, the miniature wind turbine model, and several wires, are presented in Figure 11. The multimeters are used to measure the current and voltage in the circuit when the miniature wind turbine generates electricity. While the anemometer is responsible for getting the wind speed. It's also necessary to use the resistance of 10 ohms to protect the circuit.

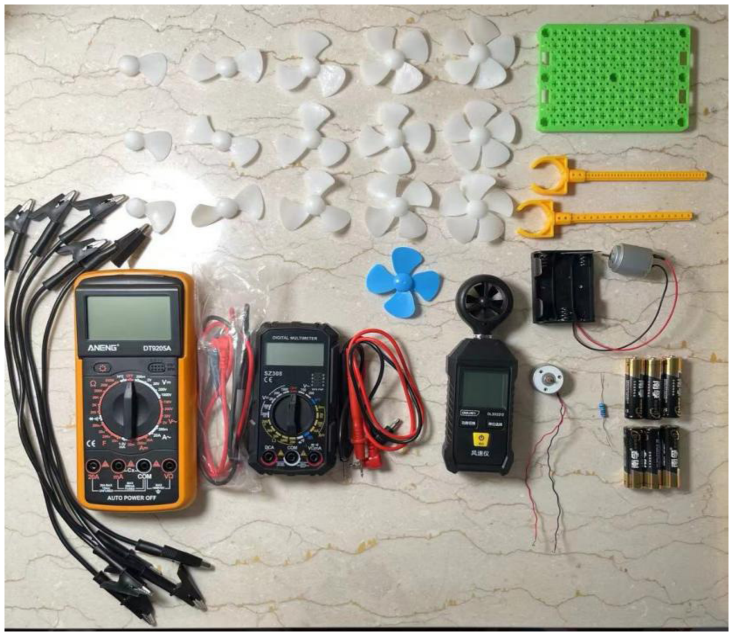

Figure 11 Experimental instruments

3.3.4 Experimental process

The experiments are carried out following these steps: Firstly, assemble the miniature wind turbine and connect the circuit. Secondly, it's important to check out if all the sections are connected well. Thirdly, fit one wind turbine blade with the generator and ensure the blade is tightly installed. The fourth step is to turn on the switch and take videos of the readings on the multimeters. This step is repeated three times for each experimental object to improve the accuracy of the measurement. At last, take down the original data from the videos and fill in the table. Following these steps, these 15 miniature wind turbines with various blade numbers from 1 to 5 at different angles (0 degrees, 30 degrees, and 60 degrees) are tested. The whole experiment is repeated three times according to the experimental principle of repetition to ensure accuracy.

4. Results

Following the principle of repetition, the original experimental data of the impacts of the number and angle of miniature wind turbines on the efficiency are collected in Table 2. The power coefficient recorded in this table is calculated from the current and voltage measured. The negative values in the table are caused by the opposite rotation direction, which would not influence the efficiency because the negative values of current and voltage will cancel each other out in formula calculations.

Table 2 The original experimental data

Angle(°) Number	0					30				60		
		Current (mA)	Voltage (mV)	C_p		Current (mA)	Voltage (mV)	C_p		Current (mA)	Voltage (mV)	C_p
1	1	0.0	0	0.0000	1	0.0	0	0.0000	1	0.0	0	0.0000
	2	0.0	0	0.0000	2	0.0	0	0.0000	2	0.0	0	0.0000
	3	0.0	0	0.0000	3	0.0	0	0.0000	3	0.0	0	0.0000
	AVG	0.0	0	0.0000	AVG	0.0	0	0.0000	AVG	0.0	0	0.0000

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2	1	9.4	95	0.0098	1	0.0	0	0.0000	1	-5.9	-60	0.0039
	2	9.0	91	0.0090	2	0.0	0	0.0000	2	-4.7	-44	0.0023
	3	8.1	83	0.0074	3	0.0	0	0.0000	3	-3.6	-32	0.0013
	AVG	8.8	90	0.0087	AVG	0.0	0	0.0000	AVG	-4.7	-45	0.0025
3	1	18.3	185	0.0372	1	0.0	0	0.0000	1	-9.0	-90	0.0089
	2	16.7	170	0.0312	2	0.0	0	0.0000	2	-8.6	-88	0.0083
	3	14.5	147	0.0235	3	0.0	0	0.0000	3	-7.7	-78	0.0066
	AVG	16.5	167	0.0306	AVG	0.0	0	0.0000	AVG	-8.4	-85	0.0079
4	1	26.1	266	0.0764	1	0.0	0	0.0000	1	-12.4	-128	0.0175
	2	27.2	276	0.0826	2	0.0	0	0.0000	2	-12.3	-123	0.0166
	3	24.3	246	0.0658	3	0.0	0	0.0000	3	-11.4	-116	0.0145
	AVG	25.9	263	0.0749	AVG	0.0	0	0.0000	AVG	-12.0	-122	0.0162
5	1	24.9	253	0.0693	1	0.0	0	0.0000	1	-8.8	-90	0.0087
	2	24.4	247	0.0663	2	0.0	0	0.0000	2	-8.4	-86	0.0079
	3	24.0	244	0.0644	3	0.0	0	0.0000	3	-7.7	-78	0.0066
	AVG	24.4	248	0.0667	AVG	0.0	0	0.0000	AVG	-8.3	-85	0.0078

In addition, Figure 12 and Figure 13 are generated from the original data, giving a clearer comparison between the figures.

Figure 12 is a scatter plot showing how the blade number affects the power coefficient. As is illustrated in the scatter diagram, as the blade number grows from 1 to 4, the power coefficient increases with increasing power coefficient differences. The highest power coefficient reaches 0.0749, which is 7.49% in efficiency when the miniature wind turbine is four-bladed, which is much larger than two times that of three-bladed miniature wind turbines (3.06%) under the same condition. In addition, a slight decrease in power coefficient exists as the blade number becomes 5.

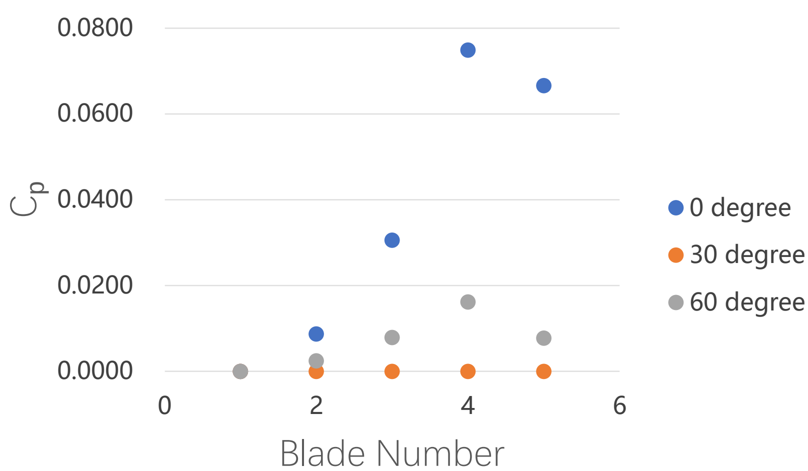

Figure 12 The impacts of the blade number on power coefficient

Figure 13 is a line chart showing the relationship between the angle and the power coefficient. The numbers shown on the right side of the graph represent the number of blades. According to the line graph, it is clear to see that miniature wind turbines with blade angles of 0 degrees have a higher power coefficient than the others. In comparison, the power coefficient is almost zero when the angle is 30 degrees. When the blade angle is 60 degrees, there's a mild increase in the power coefficients compared with those of 30-degree miniature wind turbines.

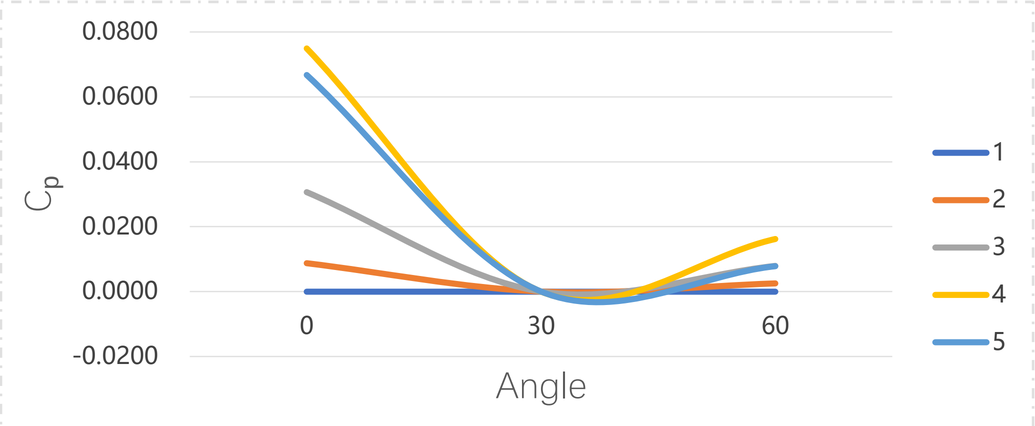

Figure 13 The impacts of the angle on power coefficient

These data demonstrate that miniature wind turbines would have better performance when having 4 blades with 0 degrees.

5. Discussion

From the experimental data, it comes to the result that for miniature wind turbines, the combination of four blades with 0 degrees is better because of higher efficiency.

5.1 Blade number

As the wind turbines become five-bladed, a slight decrease in efficiency exists. The finding of the growth of efficiency from 2 blades to 4 blades is quite similar to the research carried out by NEI et al. (2015). Since experiments are both used in the two studies, it's understandable to have similar results due to the effects of loss of charge in batteries and other factors at the experimental sites. Compared with the study carried out with the computational fluid dynamic method monolithically, the results are almost different. As mentioned in the literature review, Newbauer and Kumpaty (2012) have found that from 2 blades to 4 blades, the power coefficient decreases. The difference between these two studies is mainly caused by the difference in the primary research methods. Although the drag effects and the blade interactions are taken into account in the research with the CFD method, some other loss of energy in reality, like the inefficiency of generators, is ignored. While for experiments, all the experimental objects are tested in real life. A similar consideration of other energy dissipation is discussed in the research carried out by Sudarma et al. (2020), using both CFD simulation and experiments: the predicted efficiency in CFD is higher than the actual one because there are more unidentified losses which are not accounted for.

In comparison with the modern horizontal wind turbines, Hau(2013) has theoretically shown that the increase in blade number leading to increased output power is not linear, which is quite similar to this research. However, the power coefficient is found to have a lower rate of increase when the blade number increases in Hau's research, which is almost opposite to this research's findings. The difference is thought to exist due to mainly two reasons: Firstly, the shapes of modern wind turbines and miniature wind turbines are different from each other, which may lead to differences in the aero performance. Secondly, modern wind turbines might experience more drag effects due to their larger size compared with the miniature ones.

In terms of the cost of the wind turbines, Adeyeye, Ijumba, and Colton (2021) have concluded that the three-bladed horizontal wind turbines are a compromise of cost and efficiency. When the number of modern wind turbine blades rises, the cost of manufacturing and assembling would grow too. However, for miniature wind turbines, the cost of producing blades is relatively low, and the four-bladed miniature wind turbines are more efficient. Therefore, it's clear to see that a four-bladed design is better for miniature wind turbines while a three-bladed design is more suitable for modern horizontal wind turbines.

5.2 Blade angle

In terms of the research on the effects of angles on efficiency, this research shows blades with 0 degrees would have higher efficiency. Nevertheless, it is important to emphasize that the angle studied in this dissertation is not the same as the angles studied in other research. The previous papers focus on the angle of attack or other angles in modern wind turbine blades, while this paper takes a deeper insight into the angle between two structural lines when modeling miniature wind turbines. Therefore, this study could shed light on this corner, helping to fill the gap in the research into how angles between structural lines when modeling miniature wind turbines affect efficiency.

In addition, the combination of different research methods

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could be used to learn about the other factors of miniature wind turbine blades affecting efficiency in the future to improve the accuracy.

6. Conclusion

The dissertation sets out to discuss how the number and angle of miniature wind turbines affect the efficiency and compare the difference in effects on efficiency between modern wind turbines and miniature wind turbines.

Results of this investigation show that the increase in blade numbers from 1 to 4 would increase the efficiency, while there's a slight decrease when the miniature wind turbine is five-bladed, which is believed to exist due to higher drag effects. In addition, miniature wind turbines with 0 degrees are more efficient compared with those with 30 or 60 degrees. Therefore, the four-bladed miniature wind turbine with 0 degrees is believed to be a better design with higher efficiency. And there's no need to achieve a compromise between cost and efficiency because the production cost of miniature wind turbines is much cheaper than the modern ones. Moreover, the rate of increase in efficiency from 1 to 4 blades grows, which is opposite to modern wind turbines with the consideration of blade shape, size, and more energy loss.

The findings of this study shed light on the research into the effects of the number and angle of miniature wind turbine blades on efficiency, while other studies focus on modern wind turbines. Also, the research on the impacts of the angle between structural lines while modeling miniature wind turbines on efficiency fills the gap of this kind of angle, as others mainly take a deeper insight into the angle of attack or others.

Further studies on the area of miniature wind turbines could try to use combination methods of experiments and CFD simulation to dig deeper into the effects of other factors like weight and length of blades on efficiency.

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