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The Effect of the Number of Blades on the Characteristics of Compressed Air Wind Turbines Using R1235 Airfoil Blade Profile

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Abstract. Renewable energy is an eco-friendly, economical, and unlimited source of energy. There are several applications that have been applied in human activities using wind energy to replace fossil fuel consumption. Since most Asian countries have low wind speed areas, the design of turbine blades must be applied to generate power at lower wind speed and in unsteady conditions. Wind speed is associated with selecting the tip speed ratio (TSR), which is an important parameter in the initial design phase of wind turbines. Generally, the TSR depends on the airfoil blade profile type used, the number of blades, and other parameters. This paper aimed to study the influence of the number of blades on the performance of the compressed air application. Two-blade and three-blade wind turbines with an R1235 airfoil blade profile equipped were tested in a wind tunnel at the Research and Service Energy Center (RSEC), Rajamangala University of Technology Thanyaburi (RMUTT). The results showed that the two-blade wind turbine could perform at a higher rotational speed of 1543 rpm and maximum TSR of 10.11 at a wind speed of 6 m/s, while the three-blade wind turbine performed at a rotational speed of 1231 rpm with a maximum TSR of 9.08 at a wind speed of 5 m/s. However, the three-blade wind turbine is more appropriate to be applied for wind turbine compressed air application due to the lower cut-in speed of 3 m/s and the ability to reach maximum TSR at a lower wind speed than the two-blade wind turbine. Also, it is more suitable for operation in low-wind speed areas.

1. Introduction

Wind energy has been applied in human activities for many years. There are several applications implemented from wind energy such as pumping water, grinding grain, compressing air, and generating electricity to reduce fossil fuel consumption [1]. However, the global average on-land wind speed at 80 meters is 4.54 m/s; most wind turbines are designed to generate rated output power at wind speeds of around 10-15 m/s [2]. Therefore, low-speed wind turbines are a potential solution to operate mechanical power at low-wind energy with careful design of the airfoil blade and wind turbine characteristics, which could be expanded for the benefit of low-speed wind turbines in terms of commercial applications [3]. Hence, the low-speed airfoil blade profile, called “R1235”, has been developed by Research and Service Energy Center (RSEC) at Rajamangala University of Technology Thanyaburi (RMUTT) for wind turbines operating specifically in low-wind speed areas [4]. Also, the number of wind turbine blades could influence the performance of wind turbines, in which the most common wind turbine design is equipped with three-blade rotors. Nevertheless, the number of wind turbine blades should be designed by understanding the characteristics and application of the wind turbine for analysis in terms of performance and economics [5].

This paper aimed to investigate the influence of the number of blades on the performance of the compressed air wind turbine. Experimentation in the wind tunnel between two-blade and three-blade horizontal axis wind turbines was performed to obtain the data. The results were analyzed and compared for wind speeds of 3.5 – 7 m/s.

2. Theory

2.1. Wind Energy

Wind energy occurs from absorbing solar radiation on the earth's surface, which causes differences in temperature and pressure, thus creating moving air. Wind energy can be converted into electricity using an energy-converting machine called a "wind turbine", which harnesses the wind energy from wind flow turning the blade rotors to drive the generator and produce electricity. Wind turbines can be classified into two kinds including horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs), as shown in Figure 1. HAWTs operate as wind flows parallel to the rotating axis of the blade rotors. The benefits of these wind turbines are high power efficiency, low cut-in wind speeds, high turbine efficiency, and more economical per unit power output. The VAWTs operate as the blade rotors rotate perpendicular to the wind direction. The main advantage of this wind turbine is that the blade rotors can be operated in any wind direction, meaning yaw control would not be required. Also, it is simple for maintenance since the generator and gearbox are installed on the ground. [6].

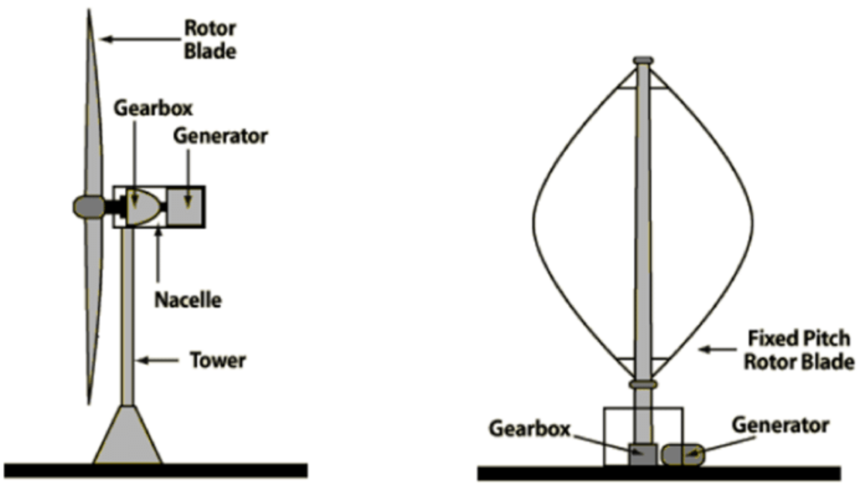

Figure 1. Left: Horizontal axis wind turbines. Right: Vertical axis wind turbines [7]

2.2. Betz's Law and Power Coefficient (Cp)

In 1919, Albert Betz discovered the "Betz limit" to explain the ideal value of wind turbine performance that extracted kinetic energy from the wind into mechanical energy. The concept could explain that the wind flow at the backside of the rotor could be restrained if all energy from the incoming wind flow were extracted to useful energy. Hence, the wind speed would reduce to zero and it would obstruct the wind movement. Therefore, the wind on the backside of the rotor must have enough wind speed to move away and allow more wind flow through the rotor. The Betz limit describes the maximum extraction of wind energy at 59% due to the wind flow through the rotor, which is reduced to the wind speed from losing energy to extraction from a turbine; the airflow requires distribution to a wider area. Also, the power coefficient is defined as being related to the Betz limit to the optimal rotor tip speed ratio of wind turbines [8]. The power coefficient could be defined as the ratio of power extracted by the turbine to the available wind power, which is given as follows [9].

$$C_P = \frac{P_T}{P_A} = \frac{Power\ output\ from\ wind\ turbine}{Power\ available\ in\ wind} \tag{1}$$

2.3. Tip Speed Ratio (TSR)

TSR is the ratio of rotor tip speed over wind speed. It is important to design the wind turbines with an optimal tip speed ratio in order to extract as much power as possible from wind energy. If the rotor rotates too slowly, it causes the undisturbed to the rotor, in which the wind flows through the space between the blades and reduces power extraction. In another way, the rotor spins too rapidly, which would appear as a solid wall, causing obstruction to the wind flow and reducing power extraction. The TSR equation could be written as follows [10]:

$$TSR = \frac{U}{V} = \frac{\omega r}{V} = \frac{2\pi r N}{60V} \tag{2}$$

Where U is rotor tip speed (m/s), V is wind speed (m/s), ω is the angular velocity (rad/s), r is the rotor radius (m), and N is the rotational speed (rpm).

A graph of power coefficient and TSR for each type of wind turbines is shown in Figure 2. Typical three-blade wind turbines contain TSR of 6-8, which provides a power coefficient of around 45%. Also, the typical small wind turbines power coefficient is around 10 – 25% [11].

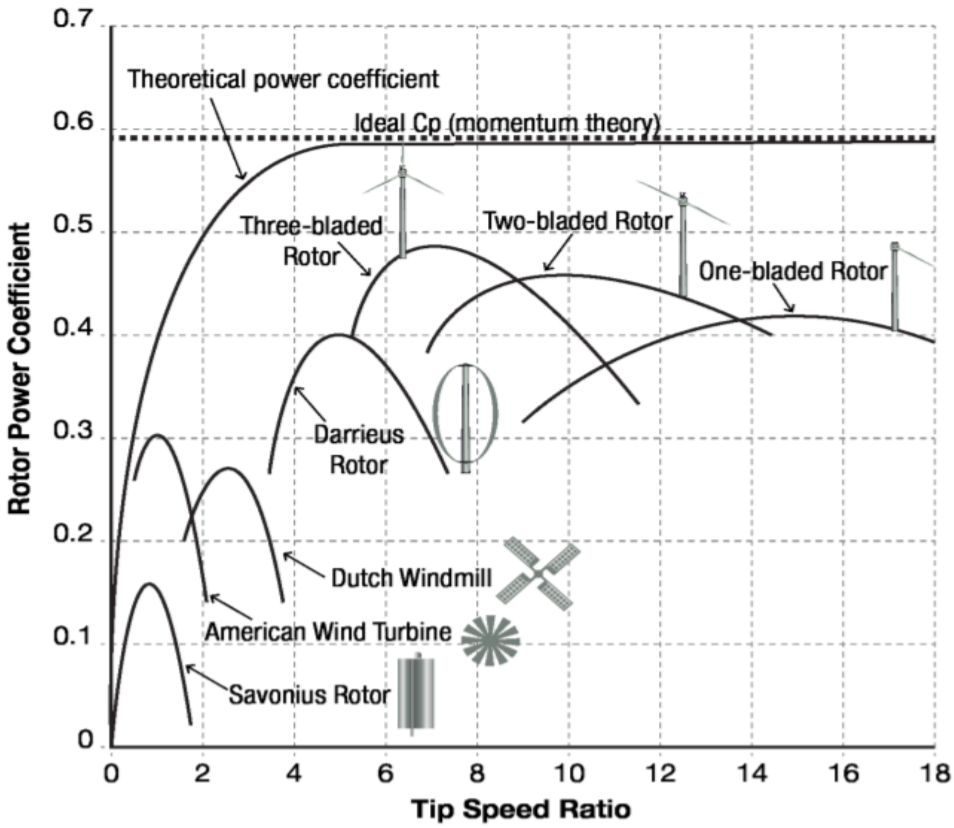

Figure 2. Comparison of the power efficiency for common types of wind turbines [11]

2.4. Wind Turbine Power Output

The power from wind energy could be captured from the effective rotor blade area of the wind turbine, given as:

$$P_A = \frac{1}{2}\rho A V^3 \tag{3}$$

Where ρ is air density (1.225 kg/m^3), A is blade swept area (m^2), and V is wind speed (m/s)
The wind turbine could not extract all the energy from wind flow as the Betz limit explains that the theoretical maximum kinetic energy of the wind could be converted into mechanical energy at 59%. The common power coefficient of the wind turbine design is around 0.35 – 0.45. The total power output from the wind turbine could be derived from equation (1), which is given as [12]:

$$P_T = \frac{1}{2}\rho A V^3 C_P \tag{4}$$

2.5. Effect of Blade Numbers

The number of rotor blades is another essential parameter that affects wind turbine performance. TSR could be optimal depending on the rotor blade numbers; a fewer number of rotor blades would provide faster wind turbine rotation. However, the power coefficient is decreased due to the rotor blades rotating too fast. [10]. Figure 3 shows a comparison between one, two and three rotor blades with respect to power coefficient and TSR. It provided that the power coefficient would be decreased as the smaller number of rotor blades at the same TSR. Most commercial wind turbines consist of two or three rotor blades, though most of the two-blade wind turbines provide higher TSR than the three-blade wind turbines [13].

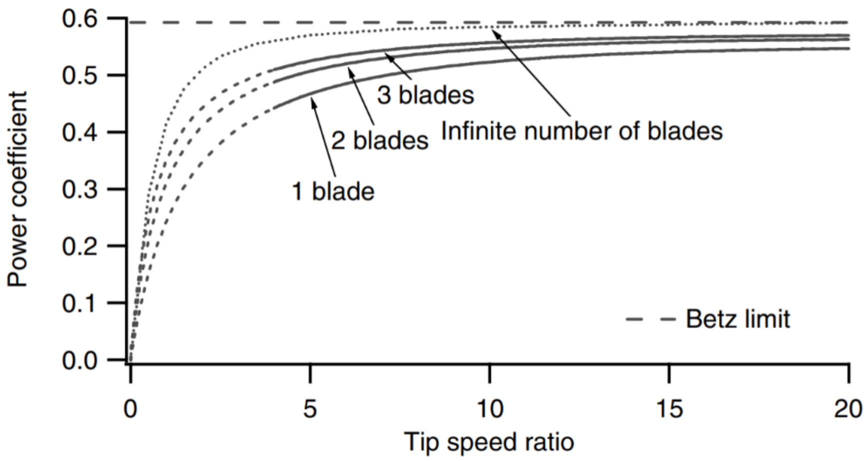

Figure 3. Optimum power coefficient for several numbers of rotor blades [13]

2.6. Compressed Air Systems

Compressed air is a form of energy storage that is integrated into several manufacturing purposes such as machinery, equipment, and processes. There are two compressed air systems, including positive displacement compressors and dynamic compressors. Positive displacement compressors could be operated based on storing the air inside the compression chamber and existing volume mechanically decreased, creating a corresponding increase in pressure prior to discharge. This system could be operated by using a reciprocating piston and rotary screws, as shown in Figure 4 [14]. The dynamic compressor's basic operation is to increase air velocity by using axial and centrifugal impeller, which is then converted to pressure at the outlet. Further classification of dynamic compressor types is radial and axial flow types, as shown in Figure 4 [15].

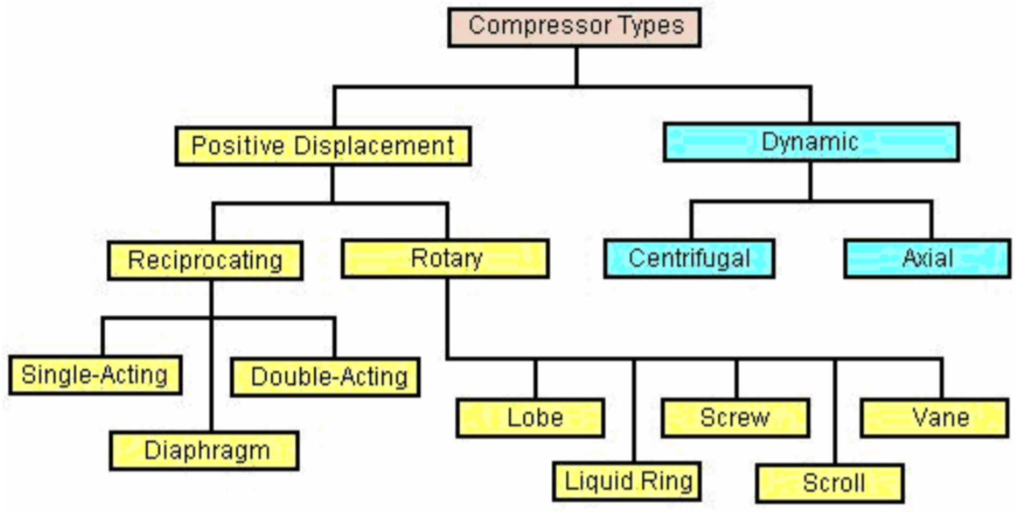

Figure 4. Compressor chart [15]

3. Materials and Methods

3.1. Experimental Setup

The aerodynamic experiments would be performed in a wind tunnel at the Research and Service Energy Center (RSEC) at Rajamangala University of Technology Thanyaburi (RMUTT). The wind tunnel contains a 20,000 CFM centrifugal fan with a wind speed controller. There are two experimental models to be tested, including two-bladed wind turbines and three-bladed wind turbines. Also, the compressed air torque load is applied to the wind turbines. The experiment investigates the wind turbine performance including rotational speed, TSR and power output between the two experimental models at 0 – 7 m/s. A schematic diagram of the wind tunnel is shown in Figure 5.

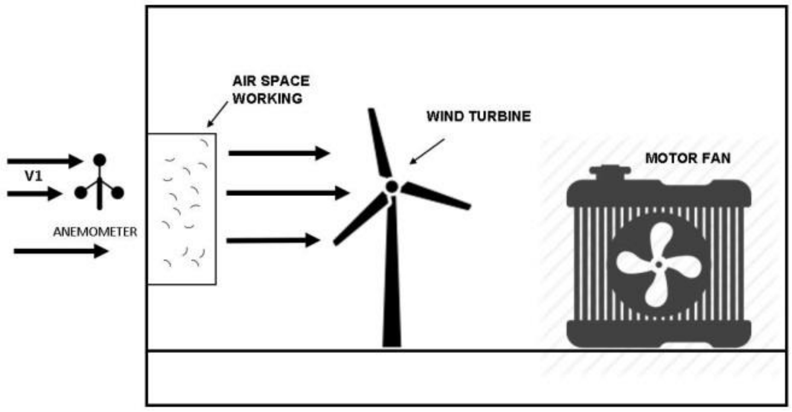

Figure 5. Schematic diagram of a wind tunnel

The wind turbines in this experiment have a blade diameter of 84 cm with a 105 cm tower height. The airfoil blade profile R1235 is specifically designed to create high lift force, which would make wind turbine to operate better in low-wind speed areas. The small-scale air compressor is mounted on top of the wind turbine to produce air pressure directly when the rotor blades are rotated. The experimental model configurations with the R1235 airfoil blade profile are shown in Figure 6.

Figure 6. Experimental models in the wind tunnel. Left: Two-blade wind turbine. Right: three-blade wind turbine.

3.2. Measurement Methods

The experimental data could be gathered by using measurement tools including an anemometer for measuring wind speed and a tachometer for measuring the rotational speed of the wind turbines, as shown in Figure 7. The wind speed could be adjusted by using the variable frequency drive of the fan motor. The tests were performed several times for measuring blade rotational speeds at different wind speeds.

Figure 7. Measurement methods

4. Results and Discussion

4.1. Variation of Power Production at Different Wind Speeds

Table 1 shows the theoretical calculations of available wind power, total power output and power output with compressed air loads. The power could be determined by using equations (3) and (4). The capacity of the power from the wind turbine used a power coefficient of 0.35. Also, the developed power of compressed air was determined by using efficient of 0.75.

Table 1. Variation of Power Production at Different Wind Speeds

Wind Speed (m/s)	Available Wind Power (Watt)	Power from Wind Turbine (Watt)	Compressed Air Power (Watt)
1	0.3394	0.1188	0.0831
2	2.7154	0.9504	0.6652
3	9.1647	3.2076	2.2453
4	21.7237	7.6033	5.3223
5	42.4291	14.8502	10.3951
6	73.3176	25.6611	17.9628
7	116.4256	40.7489	28.5242
8	173.7898	60.8264	42.5785
9	247.4469	86.6064	60.6244
10	339.4333	118.8016	83.1611

Figure 8 shows the different power production between available wind power, wind turbine power and compressed air power determined by using a theoretical equation. The available power in wind consists of higher power due to the power coefficient being neglected. However, it is impossible that the wind turbine would convert all the energy from the wind. Therefore, the wind turbine power showed that the power output results were decreased from the available wind due to the power coefficient of 0.35, which was applied in the equation to determine the actual power output of the wind turbines. Also, the compressed air load efficiency of 0.7 was applied, for which the power output from the compressed air would be decreased as an additional mechanical load was applied.

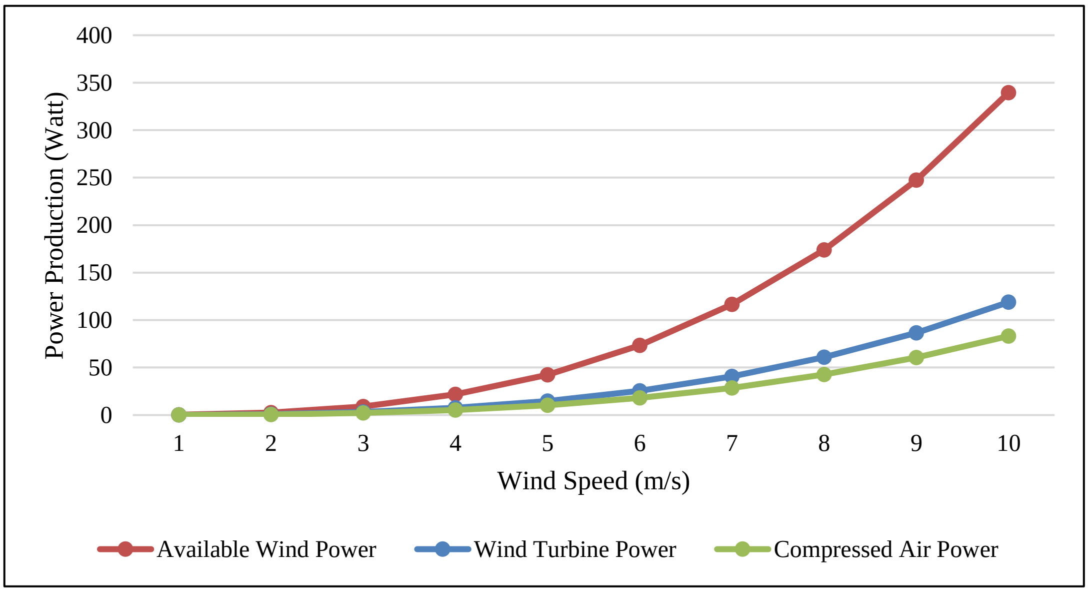

Figure 8. Power production vs. wind speed

4.2. Characteristics of R1235 Wind Turbine Blades

An R1235 airfoil blade profile was designed by Asst. Prof. Dr. Wirachai Roynarin specifically to operate in a low-wind speed area, in which the characteristics of the wind turbines are performed for high lift force with low Reynolds numbers. Figure 9 shows the comparison of C_P – TSR curve between the theoretical blade profile and the R1235 airfoil blade profile [13]. At point b to c of the curve, the data were obtained by experiment with the R1235 airfoil blade profile in the wind tunnel, while point a to b was estimated due to the incoming wind speeds being very low. Similarly, point c to d at the curve was estimated due to the limitation of the wind speeds being very high and the fixed load of compressed air load. The curve shows that theoretical airfoil blade performance dropped to zero at a TSR value of 10, while the R1235 airfoil blade profile was still operated due to the characteristics of the airfoil, which could extend the performance to a TSR value of 14 to reach zero C_P value.

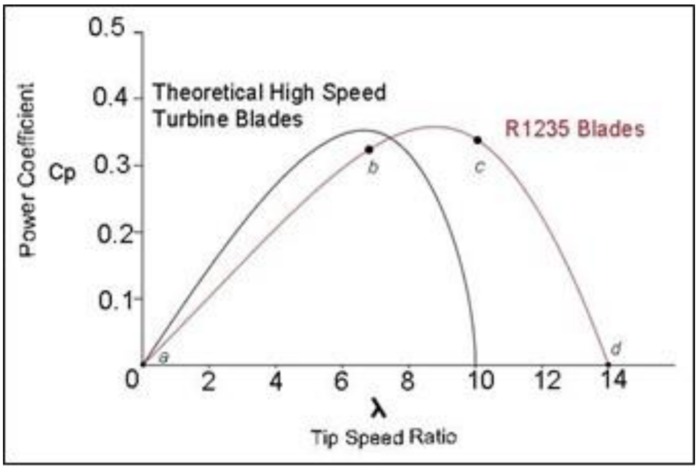

Figure 9. Comparison of the tip speed ratio between the theoretical and R1235 airfoil blade profiles

4.3. Two-Blade and Three-Blade Wind Turbine Experiment Results

The blade number of the wind turbines is a parameter to be considered for optimizing the performance of the wind turbines. The following tables represent the results obtained from the experiment in a wind tunnel with compressed air installed in the wind turbine.

Table 2 presents the two-blade wind turbine data. The wind turbine started to rotate at a wind speed of 5 m/s. The wind speed was increased gradually until it reached the maximum wind speed of 7 m/s due to the limitations and protecting the equipment from damage. The rotational speeds were increased as the wind speed increased with the maximum rotational speed of 1543 rpm achieved at 7 m/s. Also, the optimum TSR value of 10.11 occurred at 6 m/s.

Table 2. Two-blade wind turbine data

Wind Speed (m/s)	Rotational Speed (rpm)	Tip Speed Ratio
0	0	0
5	1006	8.86
5.5	1206	9.64
6	1380	10.11
7	1543	9.70

Table 3 presents the three-blade wind turbine data. The cut-in speed for the three-blade wind turbine was 3.5 m/s due to the higher blade number decreasing the wind speed to start rotating the rotor blades. The optimum TSR of 9.08 was reached at a wind speed of 5 m/s. The maximum rotational speed at 7 m/s was 1231, which was slower than the two-blade wind turbine. The results were obtained up to a maximum wind speed of 7 m/s to avoid risk to the equipment.

Table 3. Three-blade wind turbine data

Wind Speed (m/s)	Rotational Speed (rpm)	Tip Speed Ratio
0	0	0
3.5	576	7.24
4	714	7.85
5	1032	9.08
6	1086	7.96
7	1231	7.73

Figure 10 shows the comparison of C_P – TSR curve between two-blade and three-blade wind turbines. The two-blade wind turbine could reach higher TSR due to the rotational speed being faster than that of the three-blade wind turbine. However, the three-blade wind turbine could achieve the maximum TSR faster than the two-blade wind turbine, which is suitable for small wind turbines compressed air applications in low-wind speed areas.

From point *a* to *a'* and *b* to *b'*, both curves were plotted from the results obtained from the experiment in the wind tunnel. The remaining points such as *o* to *a* and *o* to *b* were estimated due to the low wind speed problems, so the points *a'* to *e* and *b'* to *f* were also estimated due to the higher wind speed and a fixed load of compressed air load.

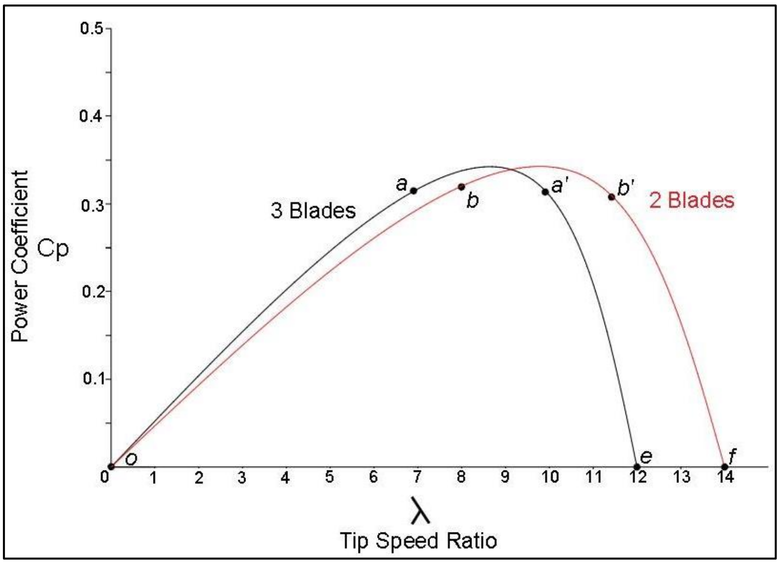

Figure 10. Two-blade and three-blade wind turbine curve performance

Conclusion

This paper aimed to investigate the influence of the number of blades on the performance of the compressed air wind turbine application. The two models of two-blade and three-blade wind turbines were tested in a wind tunnel with an R1235 airfoil blade profile equipped. The results showed that the blade numbers of the wind turbines influenced the performance of both wind turbine models. Two-blade wind turbine performance is higher than three-blade wind turbine performance in terms of rotational speed and TSR. However, the three-blade wind turbine is suitable for use in wind turbine compressed air applications in low-speed areas due to the lower cut-in speed at 3.5 m/s and lower wind speed reaching maximum TSR.

Further studies could be applied to the experimental models in a computational fluid dynamics (CFD) program to compare the results in the wind tunnel for more precise research. Also, more blades could be added to the wind turbine to investigate performance.

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