DEVELOPMENT OF SMALL WIND TURBINE USING CURVED-PLATE BLADED ROTOR -PERFORMANCE AND VISUALIZATION OF AIR FLOW USING PIV ANALYSIS

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Abstract
The authors have developed a simplified curved-plate blade of high power coefficient for small wind turbine depending on the design concept of the "Appropriate Technology (AT)". In this study, the shapes of blade are the tapered type, the straight type and the inversely tapered type and the diameter of all experimental model is 600[mm], number of blades is 5, thickness of plate is 2[mm]. The bent angles of these three types of the blades are 10, 20 and 30[deg] respectively. Blades pitch angle can be changed manually at 0, 5, 10 15, 20 and 25[deg]. In the experiment of all rotors, the wind speed in the wind tunnel is set at 10[m/s] and the torque and the corresponding to rotational speed was measured by gradually increasing the load. From the results of the experiment, the power coefficient Cp and the tip speed ratio λ were calculated to obtain the power characteristics for different blade types. In these result, the maximum power coefficient for tapered type is Cpmax=0.278 when bent angle is 30[deg] and blade pitch angle is 10[deg]. Thus, straight type is Cpmax=0.303 when bent angle is 30[deg] and blade pitch angle is 15[deg]. And inversely tapered type is Cpmax=0.338 when bent angle is 30[deg] and blade pitch angle is 15[deg]. The most efficient model was inversely tapered type. Moreover, to clarify the details of air flow around the each rotor for the maximum power coefficient, the authors conducted through visualization test using the smoke oil, high-speed camera and vector analysis using the P.I.V. system. From the visualization test and P.I.V. analysis, it was clarified that the wind speed of inflow around tip of tapered type is about 7.5[m/s], on the other hand, inversely tapered type is about 8.0[m/s]. From these results, it could presume that the latter type is more effectively converting the air flow into the shaft power than that of the former type.

Key words: Curved plate blade, coefficient of power (Cp), tip speed ratio, bending and pitch angle, P.I.V. system

1.0 Introduction
The world population is expected to grow some 9 billion around the year 2050 (Yoshifumi *et al*., 2013). Such a rapid expansion of the population will bring increase in demand for food, water, energy and pollution of the environment. Therefore, a priority issue for 21st century is to assure enough energy and water in the developing countries needed for increasing agricultural output. Development of wind power equipments will be essential in achieving these power needs. This will require the use of appropriate technology to reduce cost and localize manufacture to developing countries because such technologies are perfectly applicable to the individual conditions of the people of a particular region. The main advantage of appropriate technology is that it emphasizes on; simple design using indigenous materials at low cost while operation and maintenance are practiced by local people (Yoshifumi *et al*., 2013).

Wind energy converters that have been built over the years can be divided into two categories: the lift machines and the drag machines. Some drag based machines such as the savonius rotor may achieve maximum power coefficient of greater that 0.2 and may have tip ratios greater that 1.0, this is primarily due to the lift developed when the rotor surfaces turn out f the wind as the rotor rotates (Wilson *et al*., 1976). The choice of the airfoil, chord length and the twist along the blade determine the performance of the blade. The approach to the choice of the airfoil, chord length and twist along the blade has changed over the years (Snel, 2002). When planning to generate electricity using wind turbine, combination of wind turbines and generators to use will depend on the wind conditions, topological conditions and the energy needs of the site. Furthermore, the technological level of the region, the available type of windmills or wind turbines, and even the practices and traditions of the local people could affect the design. Since power is directly proportional to the rotor area, large wind turbines have recently become so common. This however has had a consequence on the weight of the turbine and the overall cost which increases proportionately. Technological innovation is crucial in the development of low cost and smile size turbines while still maximizing on power capture The present work is focused on the use of the concept of “Appropriate Technology” to provide customized power needs to rural Africa. Appropriate Technology refers to a technology that is best fitted to the environment and conditions of the regional society and in answering the needs there (Yoshifumi *et al*., 2013). There is an increased interest in the study of the blade shape and curvature as a way of increasing energy capture without an increase in the turbine loads (Teresa *et al.* 2011).

The maximum rotor efficiency achievable is dependent on the propulsion methods. Drag method has widely been used although it has proved inefficient since the force and rotation of the rotor corresponds to the wind direction hence as the rotor speed increases, the relative velocity of the wind is reduced. Designs that are unshielded use the curved blade shapes which have a lower drag coefficient when returning into the wind. The curved blades shapes have the advantage of working in any wind direction (Peter and Richard 2012). The power coefficient of a turbine gives the ability of the turbine to capture the energy in the wind. Its value is dependent on the Tip Speed Ratio. The Cp and TSR can be calculated using the equations 1 and 2 respectively.

Power coefficient: $C_P = \frac{2\pi n/60Q}{1/2\rho A V^3}$ (1) Tip speed ratio: $\lambda = \frac{2\pi R n/60}{V}$ (2)

Where; C_P - Power coefficient, n- Rotational speed, ρ - Air density, V - Wind speed, A - Rotor area, R - Rotor radius, λ - Tip Speed Ratio, Q - Torque

The aerodynamic lift is an alternative method of propulsion which operates on the principle that the relative velocity at which air strikes the blade is a function of the blade velocity at the radius under consideration and approximately two thirds of the wind velocity. The relative airflow arrives at the blade with an angle of incidence (*β*) dependant on these velocities. The angle between the blade and the incidence angle is known as the angle of attack (α). (Peter and Richard 2012)

2.0 Methodology

2.1.1 Blade Design

Rotor diameter of experimental models is 600 mm and number of blade is five. Blade length of curved-plate is 270 mm; thickness is 2 mm using aluminum material. In this study, the authors prepared different type of tip length, root length and bended angle of blades. Blades pitch angle can be changed manually, confirmed by protractor and rod shown in Figure 2. To change the pitch angle and bending portion, defined names and symbols are designated as in Figure 3 and Figure 4.

The 2-D designs for the straight type, tapered type and inversely tapered type curved plate blades at 10^o, 20^o and 30^o bending angles were also designed and fabricated. Each of the types was curved at 10^o, 30^o and 30^o on one side. Below is a cross sectional are of the blades when pitched at angle β and bent on one side at an angle. The plates in figures 1, 2, and 3 show the three types of blades that were fabricated. Each of the three types of blades were fabricated with bending angle of 10 deg, 20 deg, and 30 deg.

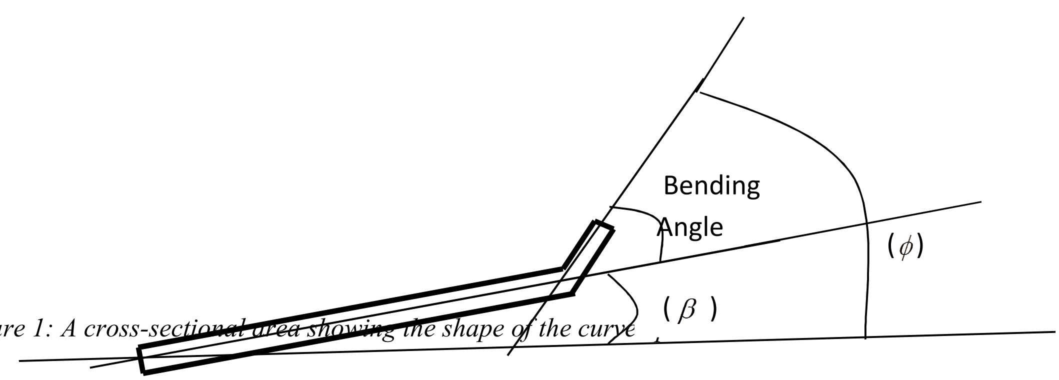

Figure 1: A cross-sectional area showing the shape of the curve

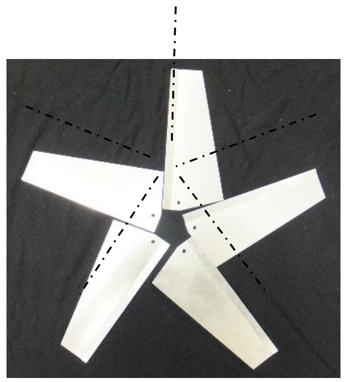

Figure 2: Tapered type aluminum curved blade

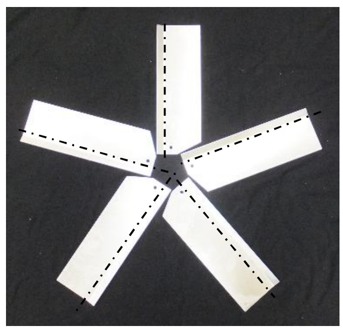

Figure 3: Straight type aluminum curved blade

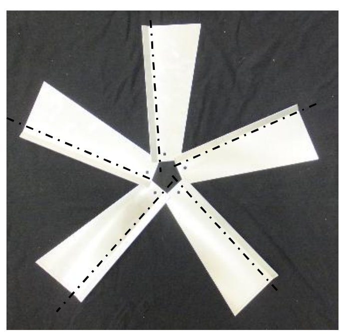

Figure 4: Inversely tapered type aluminum curved blade

2.2 Wind Tunnel Testing of the Curved Blades

The wind tunnel used in the experiment is of the Effel type with an exit of 1.05m ×1.05m. The wind speed is adjustable between 2m/s and 20m/s. An induction motor is employed as load in the experiment and the synchronized frequency is controlled by an inverter. For arbitrary determined frequencies, from high rotational speed for no load condition to lower rotational speed for gradually loaded condition, corresponding torque and rotational speed are measured by a torque converter and a revolution counter. Figure 5 shows the layout of the experimental apparatus while Figure 6 shows the turbine being tested in the wind tunnel.

In the experiment of all rotors, the wind speed in the wind tunnel is set at 10 m/s and the torque corresponding to the revolution is measured by gradually increasing the load. From the results of the experiment and using equations

1 and 2, the power coefficient Cp and the tip speed ratio λ are calculated to obtain the power characteristics for different blade types.

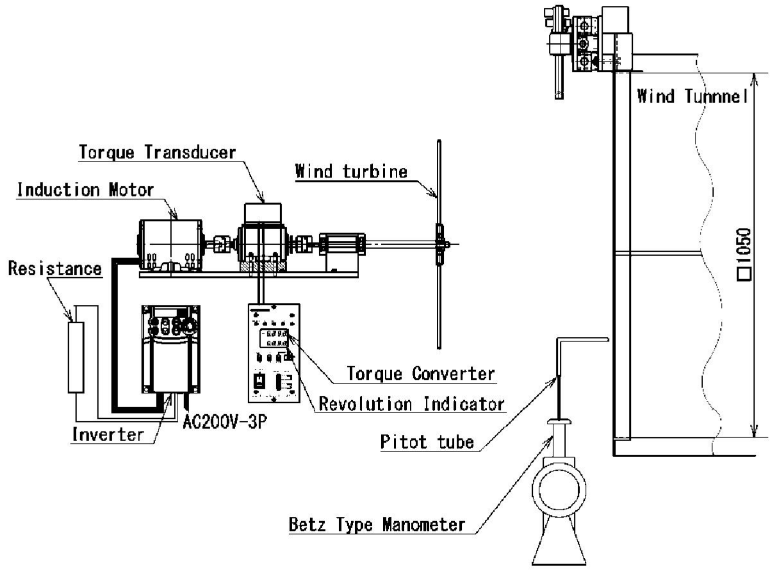

Figure 5: Schematic diagram of the wind tunnel setup

For the each of the blades curved blades, the tests were done 8m/s and 10m/s with the blades fixed at different pitch angles of 0, 5, 10, 15, 20 and 25 degrees. By the hand of angular adjustment for pitch angles is shown in Figure 6. The pitch angles were changed by turning the blades and measuring the angles using a protractor as shown in the Figure 6.

For each of the wind speeds the inverted frequency was increased to increase the rpm until there is no torque (ensuring that the 1300rpm limit is not exceeded.) The rpm was then reduced gradually while recording the corresponding torque after an interval of 50 rpm.

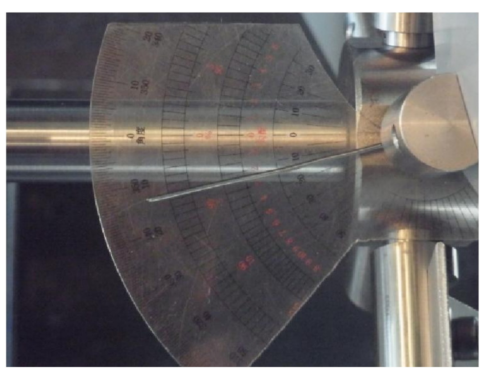

Figure 6: Mechanism of Angular adjustment

Figure 7: Turbine undergoing torque testing in the wind tunnel

2.2.1 Airflow Visualization using the Particle Image Velocimetry

Lay out of the apparatus for visualization is shown in figure 8. As visualization test, wind speed of wind tunnel set at 10[m/s]. The rotational speed of each of turbines was configured when each of experimental wind turbine get power coefficient. An induction motor is employed as load in the experiment and the synchronized frequency is controlled by an inverter.

The tracer was generated the mechanical smoke generator, discharged a smoke nozzle. A source of illumination was used Halogen lamps of number of 6. High speed camera shot these tracer, AVI files produced that in laptop computer when experimental wind turbine was rotated number of 2. These movie files were captured P.I.V system, software that done analysis of vector airflow around each experimental wind turbines.

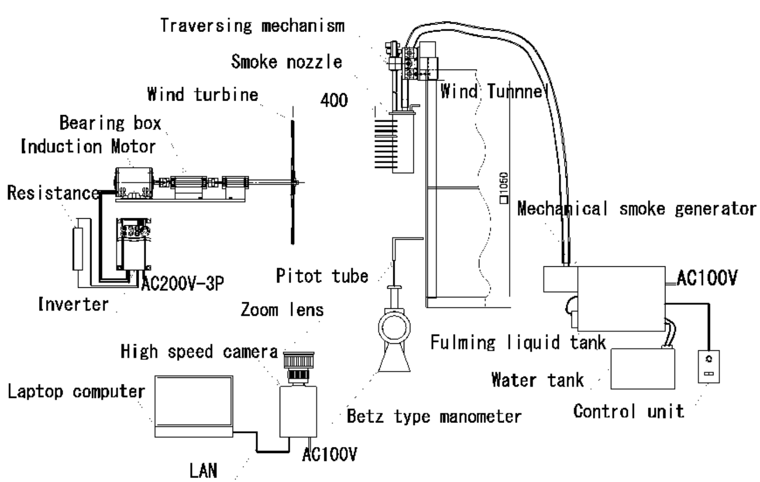

Figure 8: Layout of the apparatus for visualization

3.0 Results and Analysis

3.1 Wind Tunnel Testing of the Curved Blades

From the tunnel testing, the curved blades gave Cp maxima at the points shown in the Table 1. The overall highest Cp obtained was 0.3377 for the inversely tapered type at 10 m/s at 624 rpm and Tip Speed Ratio of 1.9603.

Figures 8 to 24 shows the power curves obtained from the experiment. From the power curves in figure 8 to figure 15 shows that the at wind speed of 8 m/s the inverse tapered type gave highest Cps followed by the straight type and finally the tapered type. For the inverse tapered type at bending angles of 10°, 20° and 30° for the highest Cps were obtained at pitch angles of 15°, 15° and 5° respectively. This shows that the angles of attack that gave the best Cp for the inverse tapered type was 25° and 35°. At the same speed, the straight type gave the highest Cps at the following pitch angles 15°, 15° and 15° for 10°, 20° and 30° bending angles respectively. This shows that for the straight type the angles of attack that gave the best Cps are 25°, 35° and 45° for 10°, 20° and 30° bending angles respectively. The tapered type gave the highest Cps at the following pitch angles 20°, 15° and 10° for 10°, 20° and 30° bending angles respectively. This shows that for the tapered type the angles of attack that gave the best Cps are 30°, 35° and 40° for 10°, 20° and 30° bending angles respectively. At 8 m/s wind speed and considering the lowest Cp values obtained. All the blade types gave the lowest Cp value at 0° pitch angle for all the bending angles of 10°, 20° and 30°.

Table 1: Results for maximum Cp coefficients

Blade type	Wind speed	Bending -pitch angles	Rpm (rad/s)	Torque	TSR	Cq	Cp	Power (W)
Straight	8 m/s	30°-15°	425	0.589	1.6689	0.1832	0.3057	26.2139
	10 m/s	30°-15°	548	0.876	1.7215	0.1761	0.3032	50.2705
Tapered	8 m/s	20°-15°	475	0.485	1.8653	0.1539	0.2870	24.1248
	10 m/s	30°-10°	601	0.719	1.8880	0.1474	0.2784	45.2513
Inversely tapered	8 m/s	30°-15°	474	0.577	1.8613	0.1812	0.3375	28.6406
	10 m/s	30°-15°	624	0.854	1.9603	0.1723	0.3377	55.8047

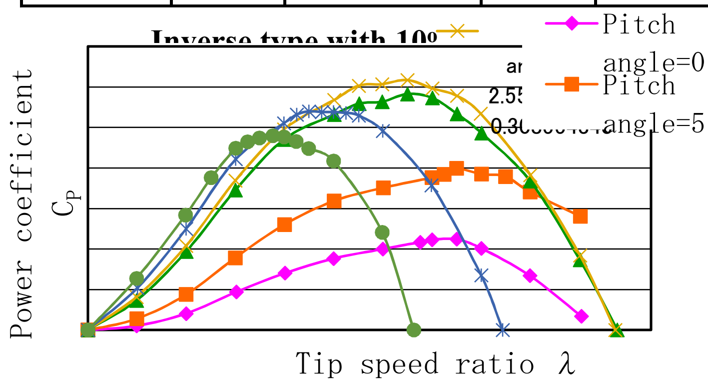

Figure 8: Power curve for inverse type at 10° bending angle and for 8 m/s

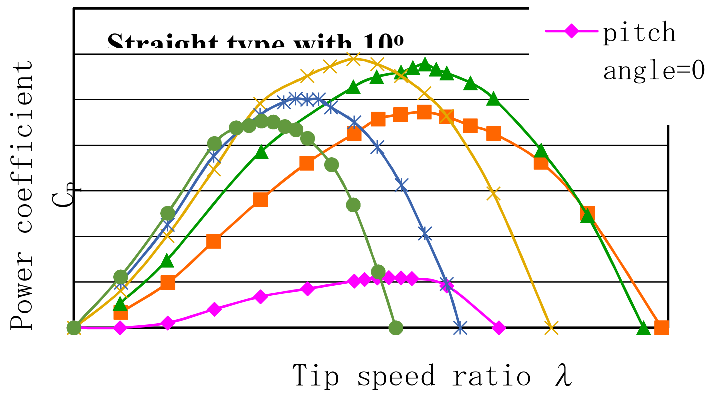

Figure 9: Power curve for straight type at 10º bending angle and for 8 m/s

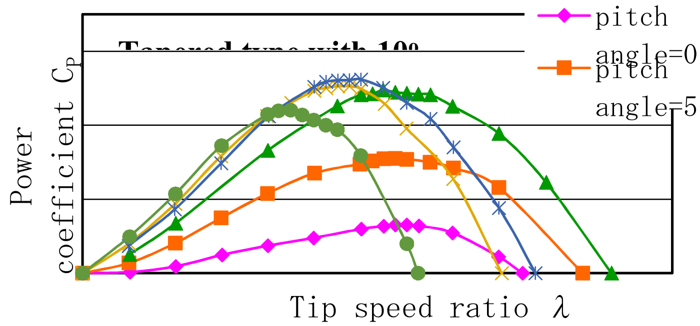

Figure 10: *Power curve for tapered type at 10º bending angle and for 8 m/s*

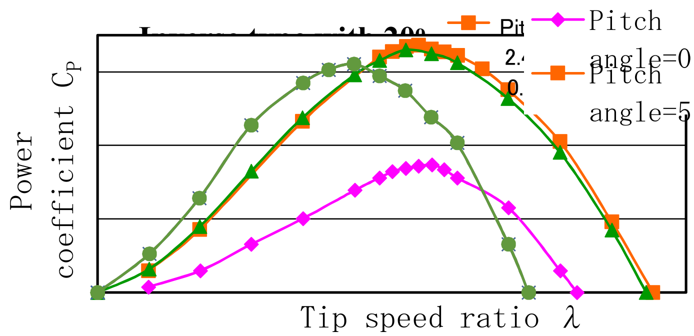

Figure 11: *Power curve for inverse type at 20º bending angle and for 8 m/s*

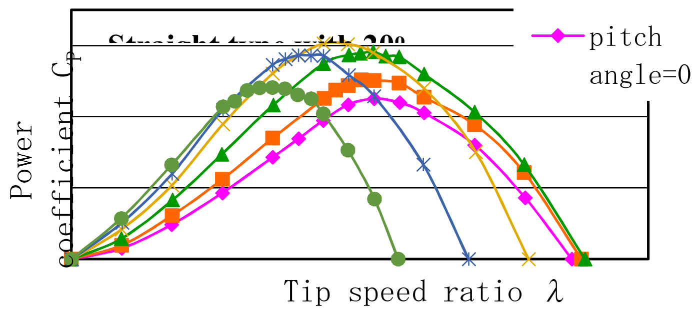

Figure 12: Power curve for straight type at 20° bending angle and for 8 m/s

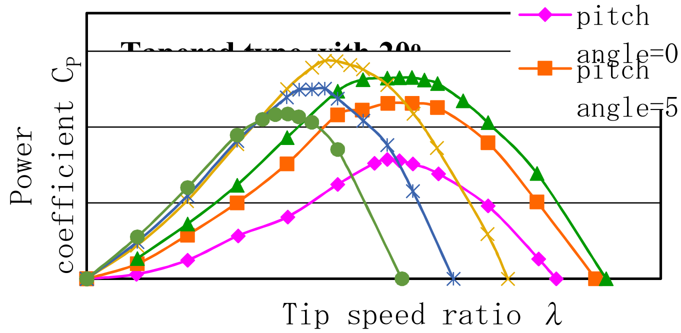

Figure 13: Power curve for tapered type at 20° bending angle and for 8 m/s

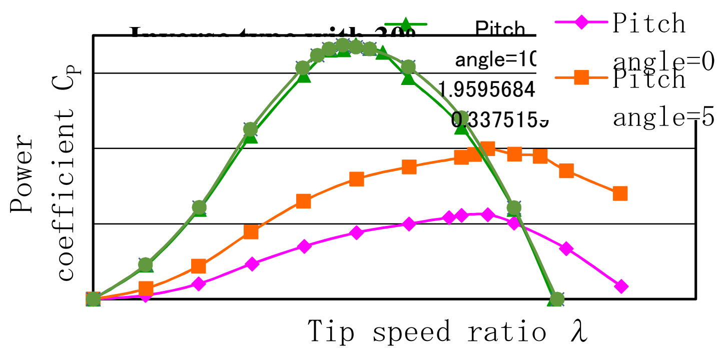

Figure 14: Power curve for inverse type at 30° bending angle and for 8 m/s

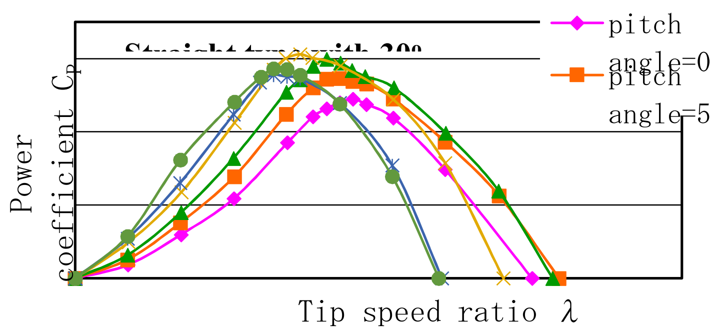

Figure 15: Power curve for straight type at 30° bending angle and for 8 m/s

From the power curves in figure 16 to figure 24 shows that the at wind speed of 10 m/s the trend was similar to the 8m/s with the inverse tapered type giving highest Cps followed by the straight type and finally the tapered type. For the inverse tapered type at bending angles of 10º, 20º and 30º for the highest Cps were obtained at pitch angles of 15º, 10º and 15º respectively. This shows that the angles of attack that gave the best Cp for the inverse tapered type was 25º, 30º and 45º. At the same speed, the straight type gave the highest Cps at pitch angles of 15º, 15º and 15º for 10º, 20º and 30º bending angles respectively. This shows that for the straight type the angles of attack that gave the best Cps are 25º, 35º and 45º for 10º, 20º and 30º bending angles respectively. The tapered type gave the highest Cps at pitch angles of 20º, 15º and 10º for 10º, 20º and 30º bending angles respectively. This shows that for the tapered type the angles of attack that gave the best Cps are 30º, 35º and 40º for 10º, 20º and 30º bending angles respectively. At 10 m/s wind speed and considering the lowest Cp values obtained. All the blade types gave the lowest Cp value at 0o pitch angle for all the bending angles of 10º, 20º and 30º.

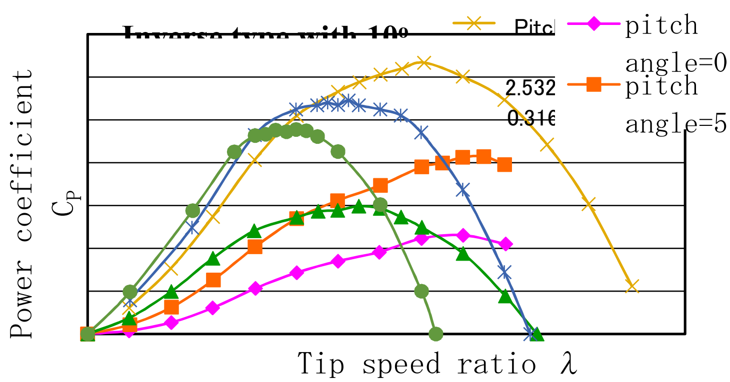

Figure 16: Power curve for inverse type at 10º bending angle and for 10 m/s

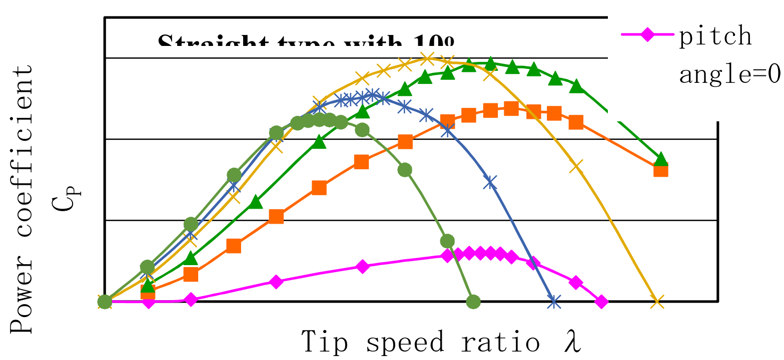

Figure 17: Power curve for straight type at 10º bending angle and for 10 m/s

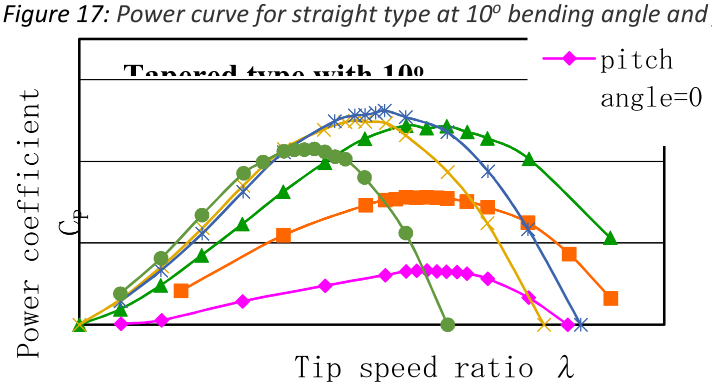

Figure 18: *Power curve for tapered type at 10º bending angle and for 10 m/s*

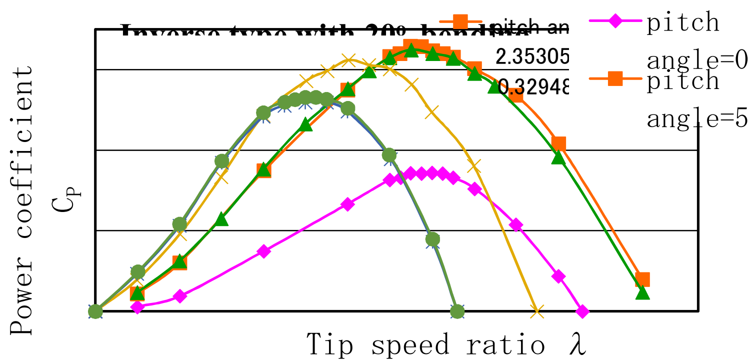

Figure 19: *Power curve for inverse type at 20º bending angle and for 10 m/s*

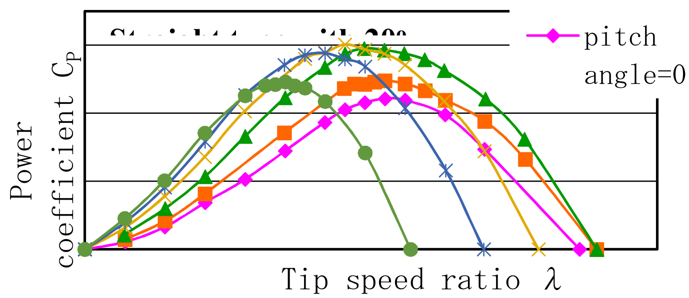

Figure 20: *Power curve for straight type at 20º bending angle and for 10 m/s*

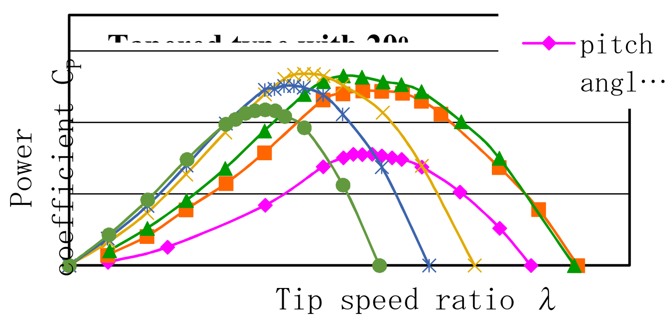

Figure 21: *Power curve for tapered type at 20º bending angle and for 10 m/s*

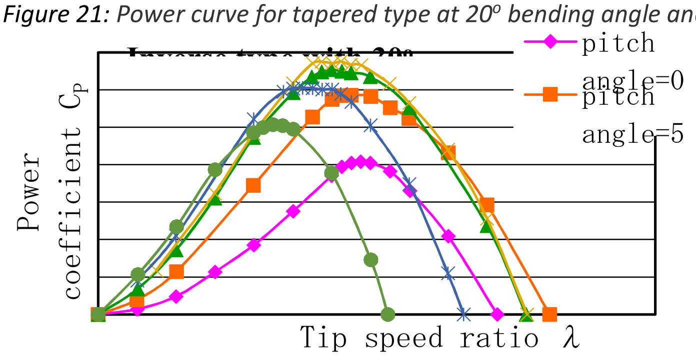

Figure 22: *Power curve for inverse type at 30º bending angle and for 10 m/s*

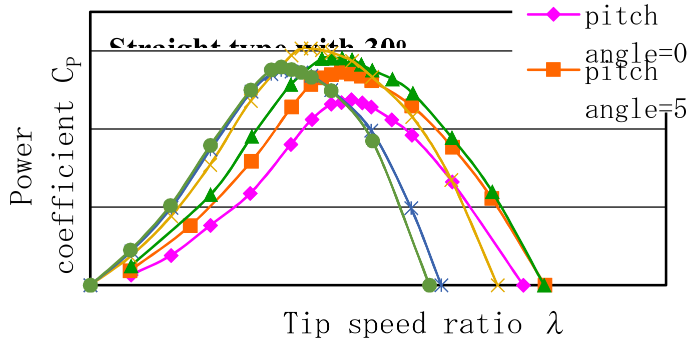

Figure 23: Power curve for straight type at 30º bending angle and for 10 m/s

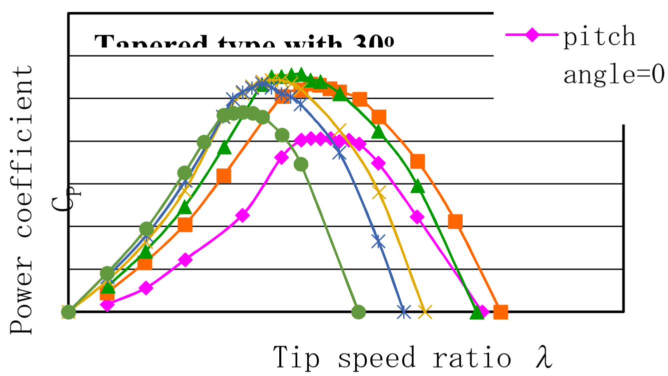

Figure 24: Power curve for tapered type at 30º bending angle and for 10 m/s

3.2 Airflow visualization using the Particle Image Velocimetry

Moreover, to clarify the details of air flow around the each rotor for the maximum power coefficient, a visualization test using the smoke oil, high-speed camera and vector analysis using the PIV system was conducted. The Vector lines of each of blade rotors were shown in Figure 25 to Figure 27, at 10[m/s]. There are the described non dimension of axial direction and span direction in these figures

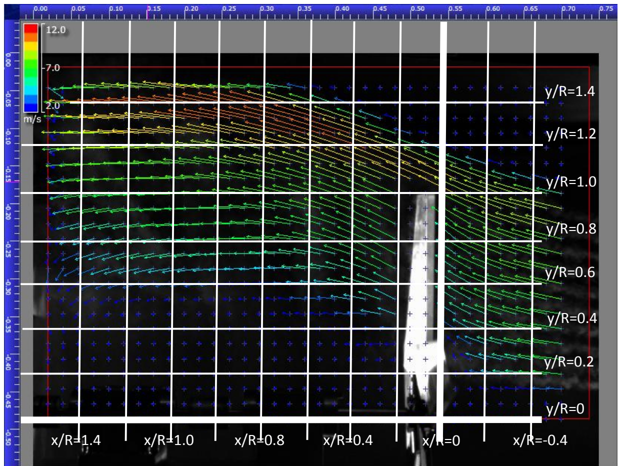

Figure 25: Vector lines of tapered blade rotor

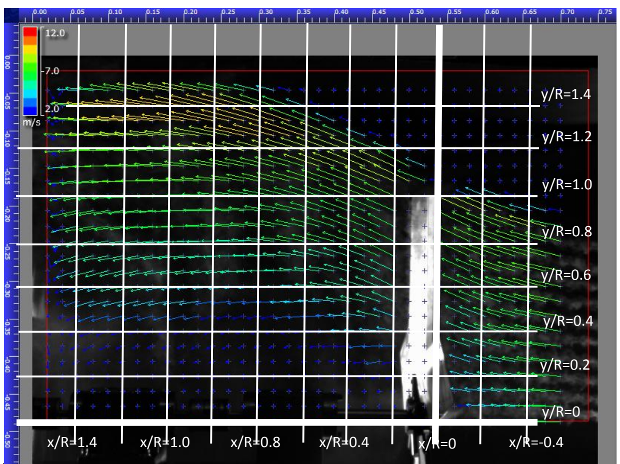

Figure 26: Vector lines of tapered blade rotor

From these figures, around area from x/R=0.2 to x/R=0, from y/R=0.3 to y/R=0.8, the inflow angle was minimum at inversely tapered blade type, above angle was maximum at tapered blade type. Therefore, around area from x/R=0.6 to x/R=1.4, from y/R=-0.2 to y/R=0.4, there is airflow in inversely tapered, but there is not airflow in tapered type. Thus, around root area, the tapered type could not extract some energy from wind, meanwhile, inversely tapered type could extract. Next, above average of vector lines, wind speed mapping of axis direction was drawn, was shown in Figure 27 to Figure 29.

From the visualization test and P.I.V. analysis, it was clarified that the wind speed of inflow around tip of tapered type is about 7.5 m/s, on the other hand, inversely tapered type is about 8.0 m/s. From these results, it could be concluded that the latter type is more effectively converting the air flow into the shaft power than that of the former type.

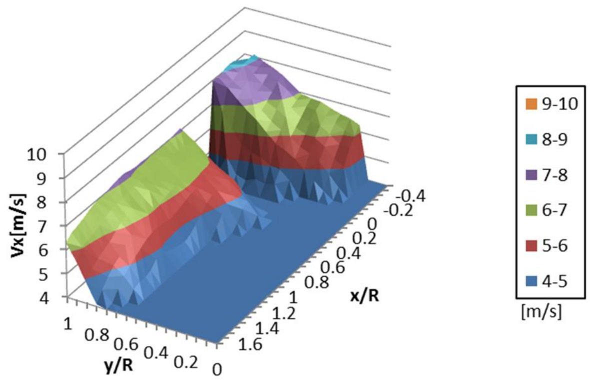

Figure 27: Vx contou

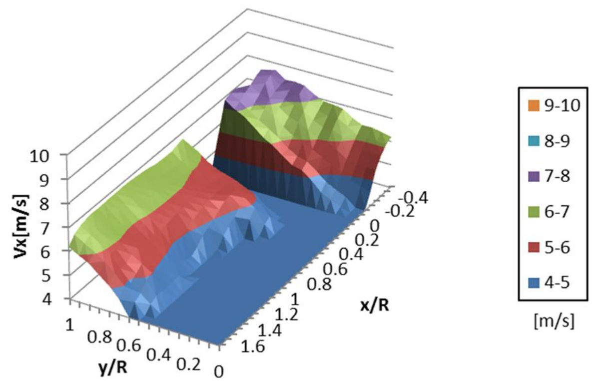

Figure 28: Vx contour of straight type

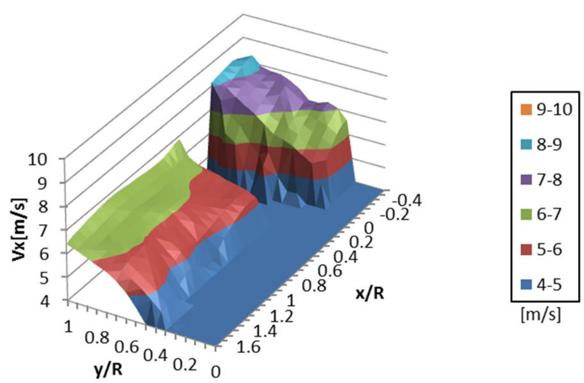

Figure 29: Vx cont

4.0 Conclusion

In this experiment, the maximum power coefficient for tapered type is Cpmax=0.278 when bent angle is 30[deg] and blade pitch angle is 10[deg]. The straight type gave Cpmax=0.303 when bent angle is 30[deg] and blade pitch angle is 15[deg] while the inversely tapered type gave Cpmax=0.3377 when bent angle is 30[deg] and blade pitch angle is 15[deg]. Therefore the most efficient model was inversely tapered type.

From the visualization test and P.I.V. analysis, it was found that the wind speed of inflow around tip of tapered type is about 7.5 m/s, while for the inversely tapered type was about 8.0 m/s. Therefore the latter type is more effective in converting air flow into shaft power than the former type.

The simplified blade for small wind turbine showed very high performance compared to precisely designed blades therefore, the curved-plate bladed rotors will have good prospect not only for developing countries but also for advanced nations.

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