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Design and Improving the Efficiency of Wind Turbines for Agricultural Purposes and Electricity Generation in a Low-wind Area

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Abstract The purposes of this study were to design, construct, test and accordingly improve the efficiency of wind turbine for agricultural purposes and electricity generation which was compatibly and effectively used in a low-wind-potential area in the western region of Thailand. Thus 2 wind turbines with accordingly horizontal axes for water pumping and electricity generating were designed. Their designs stressed the importance of simplicity rather than complexity, comfortable and easy maintenance, using domestically available materials and low cost. In order to determine their efficiency, the wind turbines were installed at 12-meter height and through mathematical models, the wind turbines' parameters of energy coefficients and aerodynamic performance were determined. Two models of wind turbines which were constructed according to the Axial Momentum Theory and the Blade Element Theory were composed of 3 wooden blades with 1.2 -meter length and 1.5-meter length.

The experimental results showed that for the Model I, it could generate the maximum electricity 259.85 watts at 6.7 m/s and for the Model II it could generate the maximum electricity 1,680 watts at 10.76 m/s Meanwhile the Model II, at maximum speed at 10.76 m/s, it could pump water at the rate of 171 L/hr.

In addition, economic worthiness analyses in terms of electricity generating cost per unit and payback period were conducted. Then they were found that for the Model I, the electricity generating cost per unit was Bht.15.63 and payback period was 38.52 years and for the Model II, the electricity generating cost per unit was Bht. 5.96 and payback period was 14.69 years. In summary, the both model of wind turbines could start electricity generating at the wind velocity at 2.0 m/s; However for the Model II, its maximum electricity power was 1,680 watts at the wind velocity at 10.76 m/s and its maximum energy efficiency was 0.33 at the wind velocity at 4 m/s. Moreover, electricity generating by a wind turbine would be interesting and worth investment if the electricity generating cost per unit were higher than Bht. 6.00.

Keywords: Wind turbine, Water pump, Economic worthiness, Payback period

Introduction

A wind turbine is an instrument which is constructed to transform wind energy into mechanical energy for different purposes: agricultural water

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pumping (Jawaid, 1981) and electricity generating, etc. (Mukhia, 1981). In Thailand, the wind turbine is mainly used in agricultural water pumping (National Energy Administration, 1984). Thus a horizontal axis wind turbine is a popular kind; however, its price is rather high because of having more blades. Therefore, to study and develop a wind turbine for local use in Thailand where the wind potential is low is of great significance. Blade design of the wind turbine is also a critical factor in terms of summoning up the energy and construction cost. Accordingly in this study impacts related to summoning up the energy from the wind turbine through changing parameters of the blade and its design to get the compatible one were to be studied and the study results would be beneficial to further relevant studies.

Objectives: This research aims to design, construct, test and accordingly improve the efficiency of wind turbine for agricultural purposes and electricity generation including economic worthiness analysis, the cost of production per unit of electrical power and payback period.

Methods

This study was consecutively conducted in 3 phases as follows:

1) Preliminary information about the wind energy capacity in the local area of Kamphaeng Saen district, Nakhon Pathom province in western Thailand was studied and the wind turbines' blade was designed accordingly that condition.

2) The Model I wind turbines design was studied and tested through the mathematical models and

3) The Model II wind turbines were redesigned, constructed and tested. After that the economic worthiness was assessed.

Related Literature

Theoretical Maximum Efficiency

High rotor efficiency is desirable for increased wind energy extraction and should be maximized within the limits of affordable production. Energy (P) carried by moving air is expressed as a sum of its kinetic energy Equation (1):

$$P = \frac{1}{2}\rho A V^3 \qquad (1)$$

Where ρ = Air Density (kg/m^3)

A = Swept Area (m^2)

V = Air Velocity (m/s)

A physical limit exists to the quantity of energy that can be extracted, which is independent of design. The energy extraction is maintained in a flow process through the reduction of kinetic energy and subsequent velocity of the wind. The magnitude of energy harnessed is a function of the reduction in air speed over the turbine. 100% extraction would imply zero final velocity and therefore zero flow. The zero flow scenario cannot be achieved hence all the winds kinetic energy may not be utilized. This principle is widely accepted (Gorban, 2001, Gasch and Twele, 2002) and indicates that wind turbine efficiency cannot exceed 59.3%. This parameter is commonly known as the power coefficient *Cp*, where max *Cp* = 0.593 referred to as the Betz limit (Lysen, 1982). The Betz theory assumes constant linear velocity. Therefore, any rotational forces such as wake rotation, turbulence caused by drag or vortex shedding (tip losses) will further reduce the maximum efficiency. Efficiency losses are generally reduced by (Lysen, 1982, Gasch and Twele, 2002):

- Avoiding low tip speed ratios which increase wake rotation
- Selecting airfoils which have a high lift to drag ratio
- Specialized tip geometries

Mathematic Model

As for the mathematical model (Lysen, 1982), in aerodynamics analysis, there are 2 theories: the Axial Momentum Theory and the Blade Element Theory and when these are merged, the performance and coefficients of the wind turbine can be found out.

1) Axial Momentum Theory explains the momentum change on the wind turbine. As shown in Figure1, given the annular tube passing through the wind turbine, at its front there is only axial velocity of the wind whereas at its back there are both axial and angular velocity of the wind.

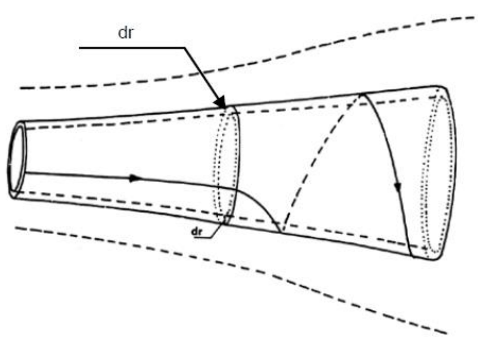

Figure 1. The wind movement behind the turbine

According to Figure 1, given the ring with the radius = r, the thickness = dr and accordingly cross-section annular tube = 2π(dr), using Bernoulli's equation to analyze the static pressure on the wind turbine where the angular velocity increasing from Ω to Ω+ω then the thrust will be:

$$dT = 4a'(1 + a')\frac{1}{2}\rho\Omega^2 r^2 2\pi r dr \quad (1)$$

And then the torque moment (Torque) on the wind turbine:

$$dQ = 4a'(1 - a)\frac{1}{2}\rho\Omega r^2 2\pi r dr \quad (2)$$

Where $a' = \frac{1}{2}\frac{\omega}{\Omega}$

2) Blade Element Theory explains the forces on small elements of each of the wind turbine blades as shown in Figure 2**.**

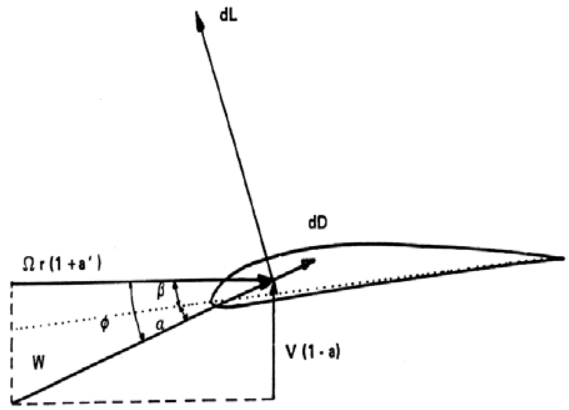

Figure 2. The wind velocity and force on the blades

The axial force and torque moment are shown in terms of lift coefficient and drag coefficient in the equations (4) and (5) respectively.

$$dT = \frac{1}{2}B_c\rho W^2(C_L \cos\emptyset + C_D \sin\emptyset)dr \quad (4)$$

$$dQ = \frac{1}{2}B_c\rho W^2(C_L \sin\emptyset - C_D \cos\emptyset)dr \quad (5)$$

From the equation (5) and the equation (6) of the torque moment coefficient, the relationship of the torque moment in terms of the differential torque can be shown as in the equation (7) of the torque moment coefficient. Then the torque moment in terms of the differential torque was:

$$C_q = \frac{Q}{\frac{1}{2}\rho V^2 \pi R^3} \quad (6)$$

$$\frac{dC_q}{dx} = 2\sigma x^2 (sin\emptyset + \lambda_r cos\emptyset)^2 (C_L sin\emptyset - C_D cos\emptyset) \qquad (7)$$

Where

$$\lambda_r = \frac{1-\frac{w}{W}tan\emptyset}{tan\emptyset+\frac{w}{W}} \qquad (8)$$

$$\sigma = \frac{Bc}{2\pi r} \qquad (9)$$

$$\frac{w}{W} = \frac{\sigma C_L}{4Fsin\emptyset} \qquad (10)$$

After receiving the differential torque coefficient then plotting graph between $\frac{dC_q}{dx}$ and λ , find C_q and calculating the power coefficient (C_p) following the equation (11)

$$C_p = C_q * \lambda \qquad (11)$$

3) Study on the lift coefficient and drag coefficient of the blades

In order to determine the energy coefficients of the wind turbines using the mathematical models, the lift coefficient (C_L) and drag coefficient (C_D) are required to be known and to be calculated. In this study a wind turbine NACA 4415 which was efficient for low wind velocity (Reuss, Hoffman and Gregorek, 1995) were applied to both two models. And the blade geometries were shown in Table 1.

Table 1. Geometries of the wind turbines

Section	Model I		Model II	
	Length (mm)	Width (mm)	Length (mm)	Width (mm)
1	150	37	150	50
2	120	25	130	37
3	100	13	120	25
4	80	10	100	13
5	70	8	80	10
6	60	7	70	8
7	-	-	60	7

Manwell, McGowan and Rogers (2009) explained there were two solution methods to find C_D and C_L at each blade section. The first one uses the measured blade characteristics and the using Blade Element Theory equations to solve directly for C_L and a. This method can be solved numerically, but it also lends itself to a graphical solution that clearly shows the flow conditions at the blade and the existence of multiple solutions. The second solution is an iterative numerical approach that is most easily extended for flow conditions with large axial induction factors. In this study the second method was used to find lift coefficient (C_L) and drag coefficient (C_D) by applying Solidworks program. The lift coefficient (C_L) and drag coefficient (C_D) were shown in Figure 3 and 4.

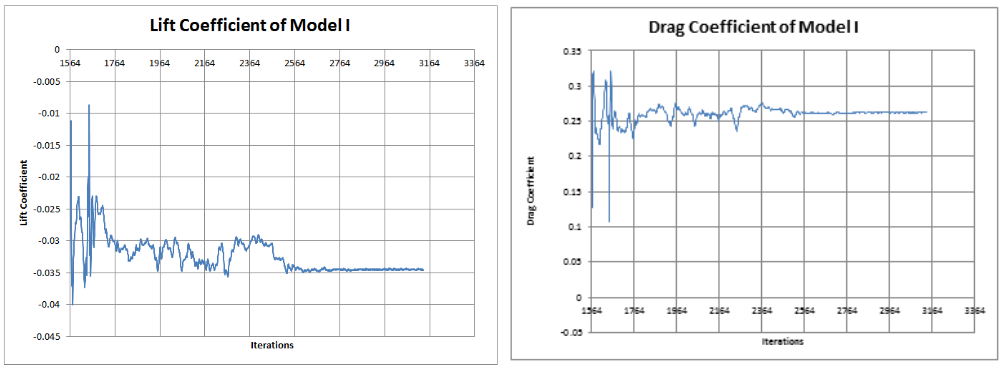

Figure 3. Lift and drag coefficient of the Model I

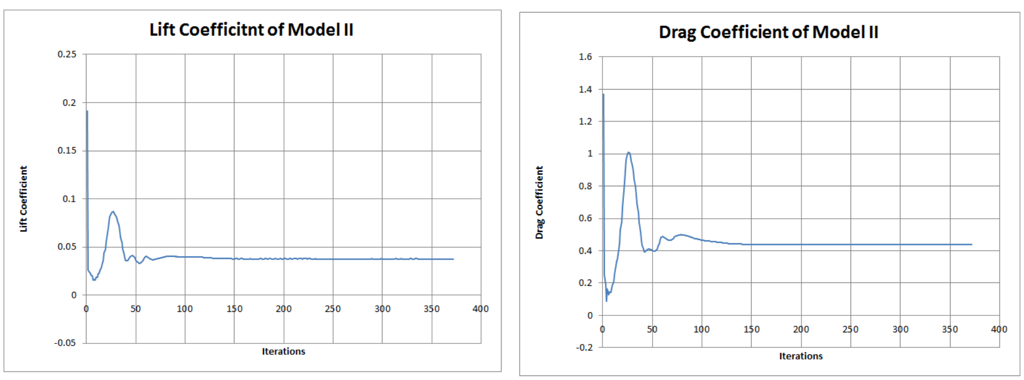

Figure 4. Lift and drag coefficient of the Model II

4) Calculation of the performance of the blade sets of the wind turbines using the mathematical models

In the analysis, the curve blades with the curve ratio of two turbine models which had both lift coefficient (C_L) and drag coefficient (C_D) were used. In testing steps of the wind turbines' performance using the mathematical models, the ratio between the blade tip speed and the torque moment coefficients at each radius from the base to apex was calculated. As for aerodynamics analysis, through combination of the Axial Momentum Theory and the Blade Element Theory, the torque moment coefficients in terms of differential (Wilson and Lissaman, 1974) could be determined as in the equations (7) - (11).

Economic worthiness analysis

Economic worthiness analysis involved electricity generating cost per unit and payback period .This was based on data and assumptions as follows: the initial cost of the wind turbines including structural construction and installation was totally Bht. 55,000; cost of maintenance was 5 % of the initial cost; the value of the wind turbine remnants at the end of use was 10 % of the initial cost; the interest rate of the loan was 7.5 %; the term of use of the wind turbines were 10 years and the unit cost of electricity used in calculation of the payback period was 4 Bht./ unit

Economic worthiness analysis can be determined using the equations (12) - (18).

$$CE = \frac{C_T}{E_a} \quad (12)$$

$$C_T = C_C + C_m - C_s \quad (13)$$

$$C_c = \text{initial cost } x \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \quad (14)$$

$$C_m = Initial\ cost\ x 0.05 \quad (15)$$

$$C_s = 0.1x \text{ initial cost } x \left(\frac{1}{(1+i)^n - 1}\right) \quad (16)$$

$$\text{payback period} = \left(\frac{Initial\ cost}{value\ of\ annually\ produced\ electricity}\right) \quad (17)$$

Where

CE = cost of electricity generating/unit (Bht./ kWh)

C_T= Total annual cost (Bht./Y)

C_c = annual initial cost resulting

C_T= Total annual cost (Bht./ Y)

n = year of turbine using

C_m = Maintenance cost (Bht.)

C_s = value of the wind turbine remnants at the end of use (Bht.)

In the analysis, the probability of wind speeds in each range can be analyzed using the Weibull distribution theory. The equation was accurately analyzed results and widely used (Gupta, 1986, Stevens and Smulders, 1979, Rehman, Halawani and Husain, 1994). The frequency distribution of wind speed can be found with the Equation (18).

$$E_a = (1 - F_C)T \int_{Vo}^{Vn} P_a(v) f(v) dv \quad (18)$$

Where E_a = produced energy from wind turbine (W-h)

$P_a(v)$ = produced energy from wind turbine (W)

V_o = cut-in speed (m/s)

V_n = cut-out speed (m/s)

F_c = the proportion of calm wind

T = hours in year

Results and Discussion

Results of Local Capacity of the Wind Energy and the Blade Design

The statistical data of the windspeed in 5 year period (2002 – 2006) at Kamphaeng Saen District (KPS), Nakhon Pathom Province are shown Figure 5.

The analysis of wind speeds at a height of 12 meters, in evaluating the results of frequency analysis of wind speeds throughout the year, using the equation of Weibull, the results is shown in Figure 6. The graph can be noted that the distribution of wind speed will be tightness in the wind 3-5 m/s.

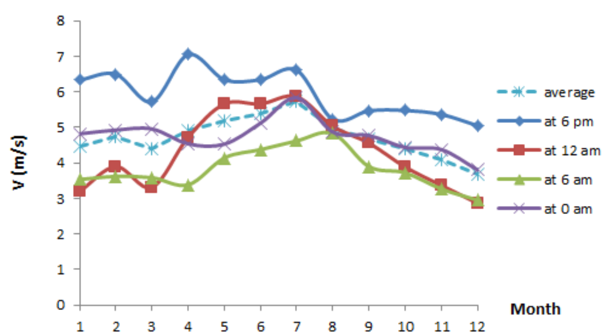

Figure 5. Monthly wind speed at KPS (2002-2006)

The first wind turbines was designed according to NACA (Wilson and Lissaman, 1974) which was so efficient for lower wind velocity, for average wind speed was 3 – 5 m/s at the of 12-meter height with having tip speed ratio of 6 of 3 wooden blades of 2.4-meter diameter (Figure 7). Analyzing by Solidworks program for the strength, the result was in Figure 8. Turbine frame was made of steel with a thickness of 10 mm to be lightweight, durable and easy to maintain. Generator was made from electricity wire No. 15AWQ of 80 rounds of ten-coil-magnet series, magnet type was Neodymium with size of 30-mm outside diameter, 15-mm inside diameter and 10- mm thickness. Magnet series were put on the steel plate diameter 304.8 mm and the rudder was used to control the turbines when the wind speed exceeds 20 m/ s to prevent damage.

Wind turbines were installed 12 m above the ground. The tested result was shown in Figure 9.

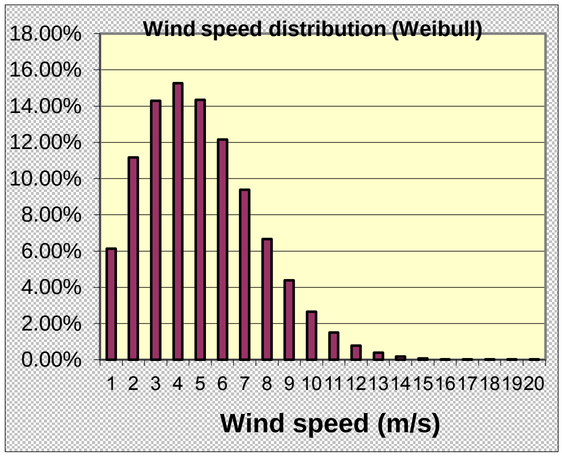

Figure 6. Frequency distribution of wind speeds at a height of 12 m.

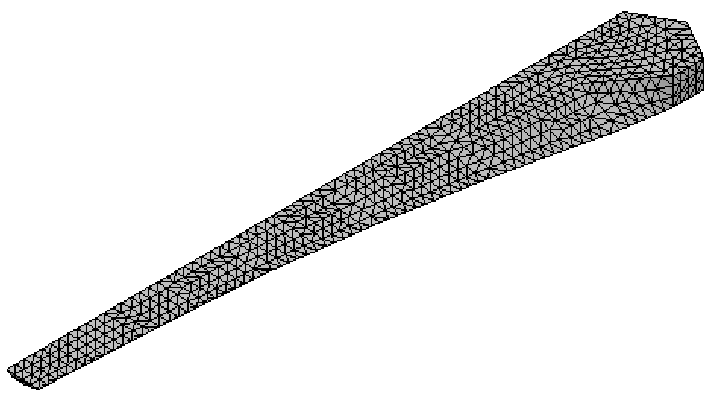

Figure 7. Wind Turbine Blade Model I

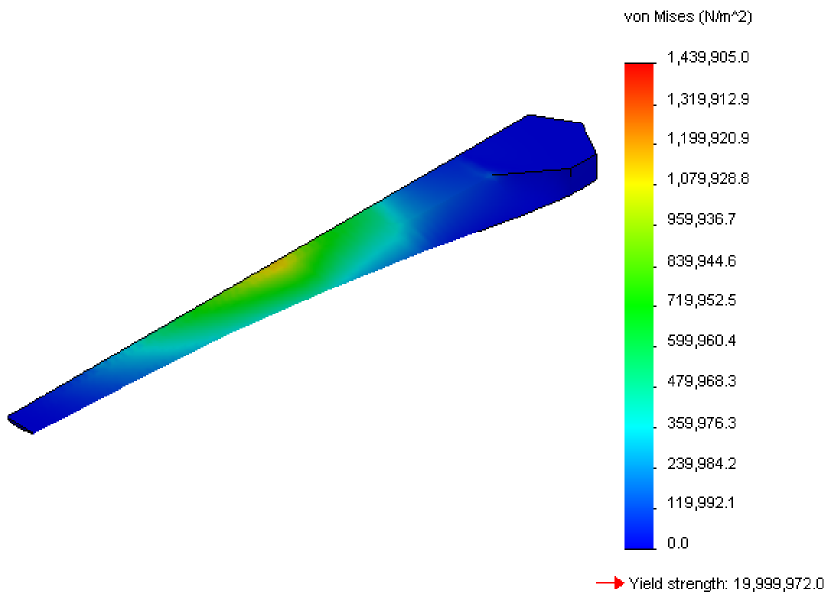

Figure 8. Strength analysis of the Wind Turbine Blade Model I

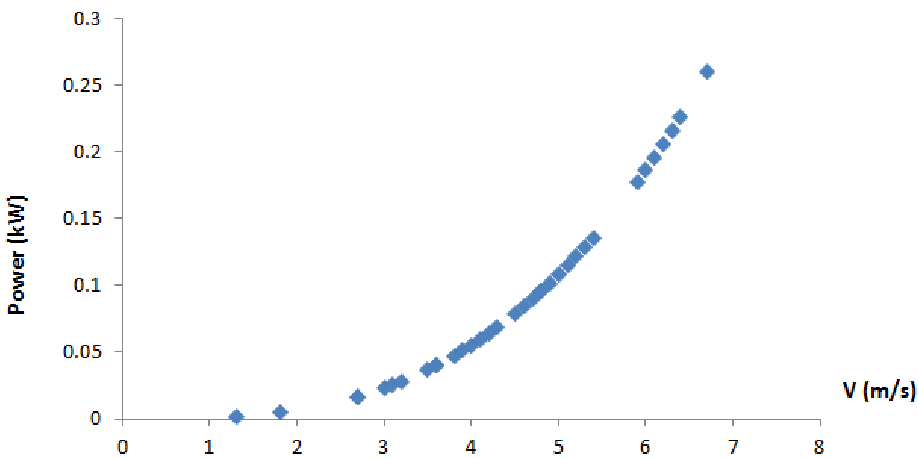

Figure 9. Experimental Power from Wind Turbine Blade Model I

Blade improvement for agricultural wind turbine

The rotors on modern wind turbines have very high tip speeds for the rotor blades. In order to obtain high efficiency, it is therefore essential to use blades with a very high lift to drag ratio. This is particularly necessary in the section of the blade near the tip, where the speed relative to the air is much higher than close to the centre of the rotor.

From Figure 3, we found that C_D and C_L of the model I can be improved in order to get better result of generating electricity and for one more purpose of water pumping so the Model II wind turbine blades with tip speed ratio of 7 and 3 - meter diameter, were redesigned (Figure 10). Comparing the C_L / C_D ratio of wind turbine Model I and Model II (Figure 3 and Figure 4), we found that the C_L / C_D ratio of wind turbine Model II was increasing 65%.

The turbines were analyzed in terms of strength (Figure 11), comparing the strength of wind turbine Moedl I and Model II (Figure 8 and Figure 11) , we found that the critical point of Model I was on the middle of trailing edge of the blades, the maximum stress was 1,439,905 N/m^2. But for the Model II, the critical point was at the beginning of trailing edge near hub area, the maximum stress was 574,787 N/m^2, the strength of Model I was almost three times the strength of Model II.

After that the wind turbine Model II was tested (Figure 12), and the results shown in Figure 13, comparing the power of wind turbine Moedl I and Model II (Figure 9 and Figure 13), we found that the maximum power of Model I was 259.85 watts at 6.7 m/s. But for the Model II, that the maximum power was 1,680 watts at 10.76 m/s.

Figure 14 shows the power coefficient. The maximum of power efficiency was 0.33 at the wind velocity at 4 m/s. Figure 15 shows the capacity for water pumping driven by wind velocity for 4-m water head with the cylinder size 25.4 mm-diameter, water pipeline size 32-mm diameter and stroke of 70mm-length. At maximum speed at 10.76 m/s, it could pump water at the rate of 2.85 L/min.

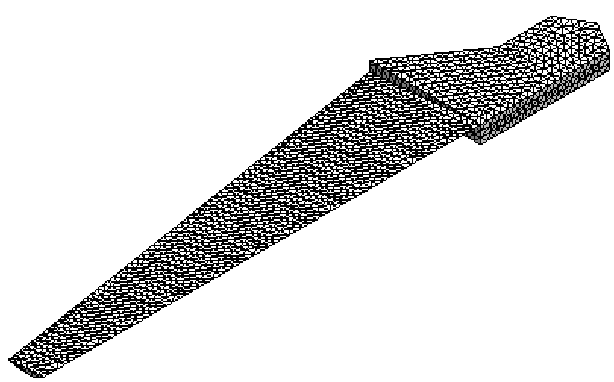

Figure 10. Wind Turbine Blade Model II

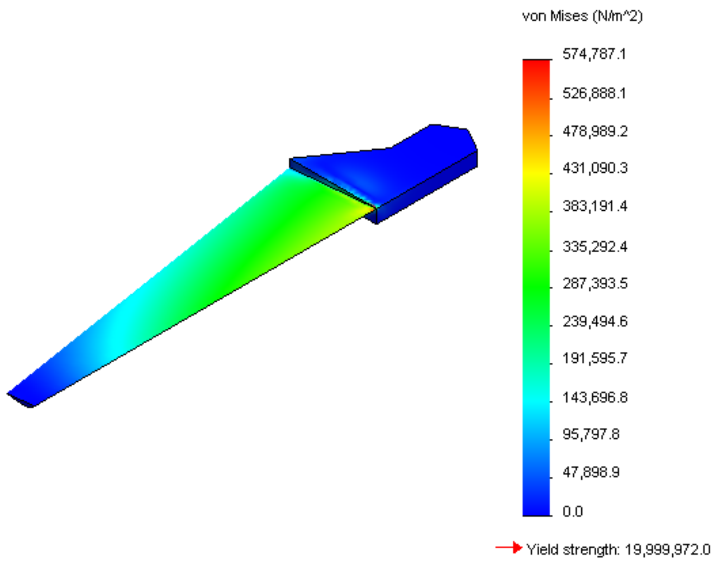

Figure 11. Strength analysis of the Wind Turbine Blade Model II

Figure 12. Wind Turbine Constructions

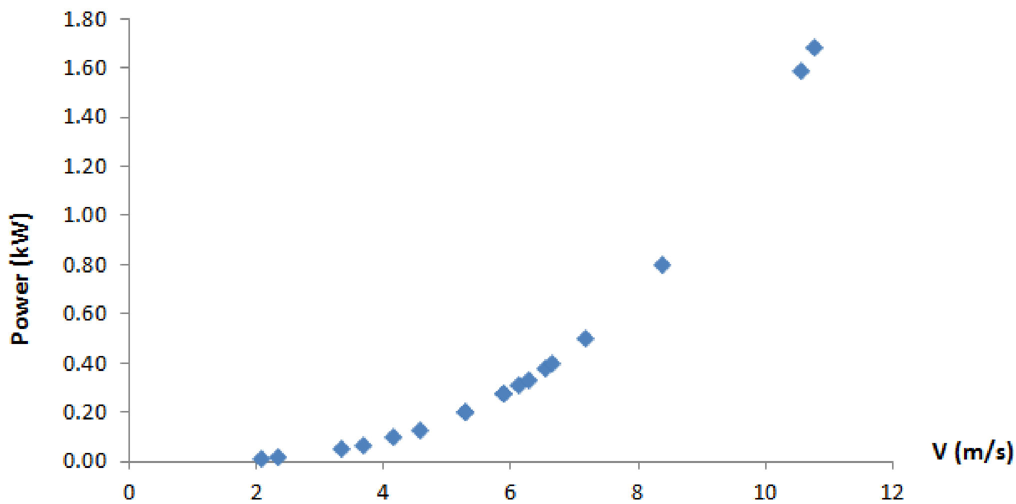

Figure 13. Experimental Power from Wind Turbine Blade Model II

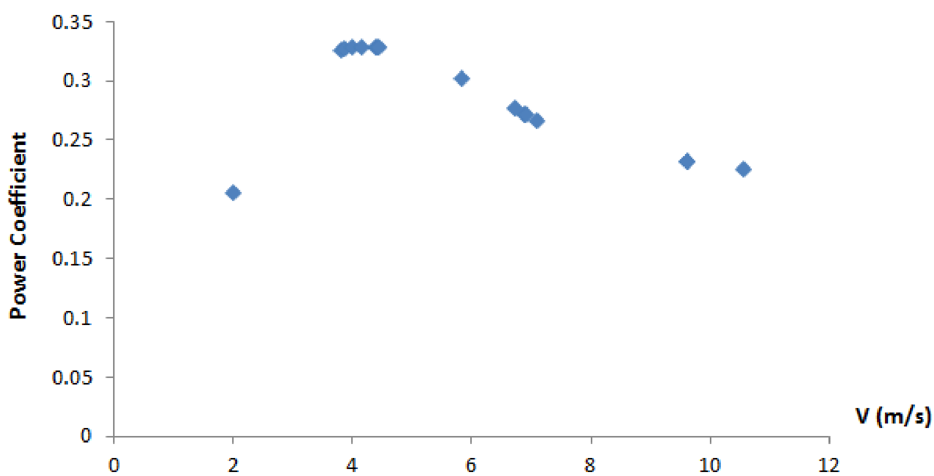

Figure 14. The power coefficient capacity from Wind Turbine Blade Model II

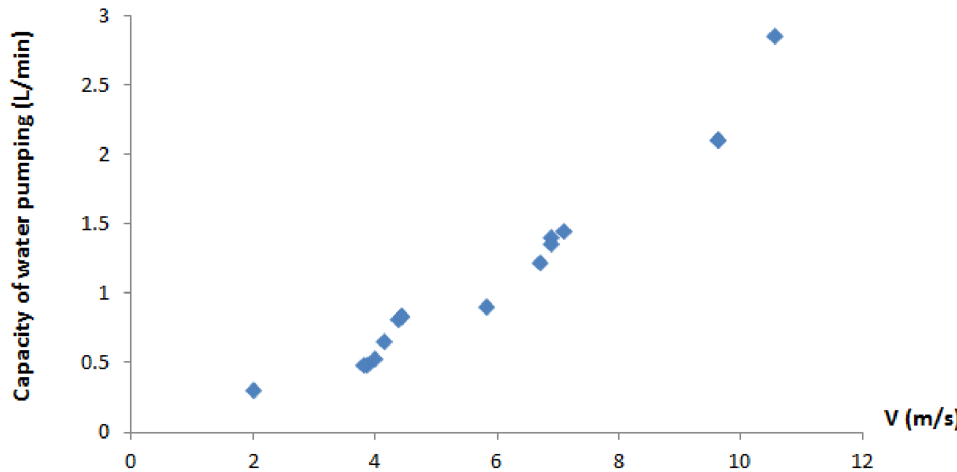

Figure 15 .Experimental water pumping capacity from Wind Turbine Blade Model II

Economic Worthiness Analysis

The economic worthiness analysis of the wind turbines for electricity generating was shown in Table 2.

Table 2. Economic Worthiness Analysis

	Item	Model I	Model II
1	Initial cost of the wind turbine construction, baht	55,000	55,000
2	Annually Initial cost (C_c), baht /year	8,012.7	8,012.7
3	Annual maintenance cost (C_m), baht/year	2,750	2,750
4	Annual value of the remnants (C_s), baht/year	5,183.6	5,183.6
5	Total annual cost (C_T),baht/year, (2)+(3)-(4)	5,579.1	5,579.1
6	Total annual electric power obtained, kWh/year	357	936
7	Annual value of the electric power, baht/year, 4x(6)	1,428	3,744
8	Generating cost of the electric power, Baht/kWh, (5)/(6)	15.63	5.96
9	Payback period*, year, (1)/(7)	38.52	14.69

Conclusion

The experimental results showed that for the Model I, it could generate the maximum electricity 259.85 watts at 6.7 m/s and after making an improvement for the Model II, it could generate the maximum electricity 1,680 watts at 10.76 m/s. Meanwhile the Model II, at maximum speed at 10.76 m/s, it could pump water at the rate of 2.85 L/min. or 171 L/hr.

For economic worthiness analyses in terms of electricity generating cost per unit and payback period were conducted. Then they were found that for the Model I, the electricity generating cost per unit was Bht.15.63 and payback period was 38.52 years and for the Model II, the electricity generating cost per unit was Bht. 5.96 and payback period was 14.69 years. In summary, the wind turbine Model II could start electricity generating at the wind velocity at 2.0 m/s; its maximum electricity power was 1,680 watts at the wind velocity at 10.67 m/s and its maximum energy efficiency was 0.33 at the wind velocity at 4 m/s. Moreover, electricity generating by a wind turbine would be interesting and worth investment if the electricity generating cost per unit were higher than Bht. 6.00.

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