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Original Article

Optimum pitch angle of downwind Thai sail windmill for maximum annual energy production

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Abstract

The traditional Thai sail windmill (TSW) has been a workable machine for centuries and is used mainly to pump water for agriculture, but it suffers from low operating efficiency in the order of 10%. For a wind turbine, pitch angle and wind statistics are significant parameters which affect efficiency and annual energy production (AEP). The optimum pitch angle depends on the local wind statistics. The pitch angle of the TSW is typically designed using rules of thumb,, which have been carried on from one generation to the next. Therefore, the optimum design features have not been systematically confirmed. The objective of the current study is to investigate the optimum pitch angle of a TSW by a systematic experiment in order to obtain the maximum AEP. The test model was built similarly to a TSW but scaled down 8 times and the rotor orientation was changed to downstream (DTSW model) to catch the wind more easily. The experiment was performed by the tow testing method. The Weibull function was used for the AEP estimation in the Nakhon Ratchasima Province of Thailand as a case study. The results showed that the optimum pitch angles of the 4-blade and 6-blade DTSW models were 5 and 10 degrees and the maximum efficiencies were 17% and 25% and produced AEPs of 20.4 kW-hr and 37.3 kW-hr, respectively.

Keywords: Thai sail windmill, pitch angle of wind turbine, annual energy production, low cost wind turbine, Weibull function

1. Introduction

The Thai sail windmill (TSW) has been used for centuries in Thailand for agricultural purposes to pump water to rice fields and to pump brine water for salt farming. Mukhia (1981) is perhaps the first to research the operation of the TSW. A TSW is a horizontal axis wind turbine which presents the rotor upstream, which is called an upwind type without a yaw system. A full scale TSW commonly has a diameter of 8 meters with 6 blades. The blade material is made of canvas and tailored in a triangular shape (Figure 1a). Recently, Thep-wong (2013) studied a small scale TSW and found that the average efficiency was only about 10%. In recent years, there various publications have talked about the effect of pitch angle to the wind turbine efficiency (Sudhamshu *et al.*, 2016; Thumthae & Chitsomboon, 2009; Wei, Pan, & Liping, 2015).

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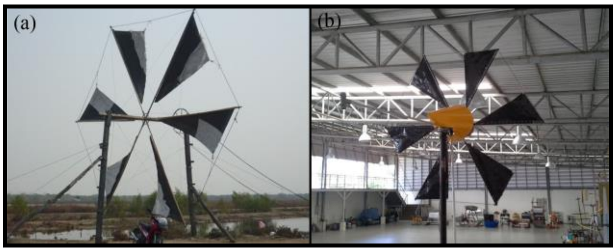

Figure 1. Thai sail windmill (TSW)
(a) Conventional TSW (b) DTSW model.

For the TSW, there is no research on the optimum pitch angle to enhance the efficiency and annual energy production (AEP). Generally, a farmer will design a TSW using rules of thumb which may not be the best way to obtain a true optimum pitch angle. The main objective of the current study was to investigate the true optimum pitch angle by a systematic experiment to maximize the AEP. The model was built in a similar fashion to the TSW but scaled down 8 times and the rotor orientation was changed to downstream, called the downwind type, so that the rotor can yaw by itself (Gipe, 2004; Kress, Chokani, & Abhari, 2015) and help add to the AEP. Tow testing (Maughmer, 1976; Spera, 1998) is a method to test a wind turbine by mounting the wind turbine on a moving vehicle. This method was performed for this research since a suitable wind tunnel was unavailable. The Weibull function was used to represent the wind velocity probability distribution for the AEP estimation. For this study, the scale (c) and shape (k) parameters in the Weibull function of the Nakhon Ratchasima Province of Thailand were used for a case study.

2. Materials and Methods

2.1 Test models

Because a full scale TSW is too large to install on a tow vehicle (pick-up truck), the models had to be scaled down from 8.0 meters to 1.0 meter. The original TSW rotor orientation was changed from the upwind type to the downwind type (DTSW model) so the rotor can have a yaw mechanism by itself (Gipe, 2004; Kress, Chokani, & Abhari, 2015) (Figure 1b). The conical angle is a parameter for a downwind wind turbine. It is the angle between a rotor plane and a spar inclining in a little angle toward the downwind direction to adjust the yaw ability. For this study, the conical angle of the model was solely set to be zero. The blade material of the TSW was made of canvas and tailored as a triangular shape. The model was built in two configurations that consisted of 4-blade and 6-blade models which had the dimensions of 44.3 ×25.5 cm)/blade and 40.0×18.7 cm/blade, respectively, that followed the form of length×height/blade (Figures 2a, 2b). When the solidity was calculated, both models had a solidity of about 28%. Solidity is an important parameter for every wind turbine. It is the ratio between the blade projected area and rotor plane area (Burton, Jenkins, Sharpe, & Bossanyi, 2011). The pitch angles of TSW are not constant along the span radius because the TSW blade has an automatic twisting behavior. Therefore, the pitch angle referred to in this research means the pitch angle at the blade tip (**β**) (Figure 3). It should be noted that this pitch angle is just a superficial angle because the true pitch angle should be different when the rotor is rotating. The efficiencies and AEPs of the downwind Thai sail windmill model in this study were examined at 4 pitch angles: 5, 10, 15, and 20 degrees.

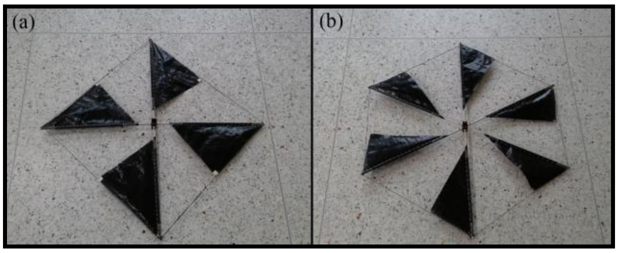

Figure 2. Rotor model
(a) 4-blade rotor (b) 6-blade rotor.

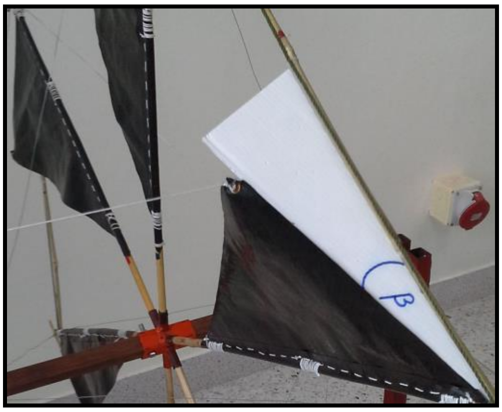

Figure 3. Pitch angle.

2.2 Test procedure

A steel rack was installed on the bed of a pick-up truck to fasten the rotor and accessories such as spring balances, speed sensor, and anemometer (Figures 4a, 5). The rotor was placed 2.5 meters away from the top of the vehicle's roof. This height was enough to avoid the wake of air flow over the roof top. The anemometer was placed 1.0 meter in front of the rotor plane. The testing procedure is explained briefly.

- The steel rack, rotor, and all accessories were installed on the vehicle.

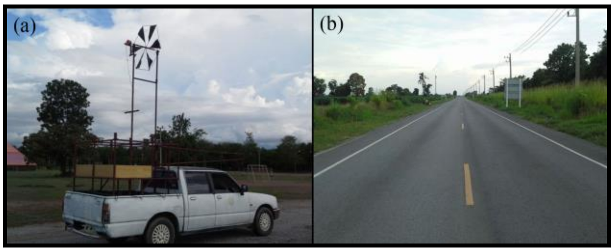

Figure 4. Tow testing
(a) Steel rack on a vehicle (b) Route for testing.

Figure 5. Equipment installed.

- While monitoring the local wind, the vehicle started moving only if the local wind did not exceed 5% of the testing speed.
- The vehicle moved at a constant speed on a straight route without slopes (Figure 4b). The speed of the vehicle was almost the same as the free stream velocity in a wind tunnel.
- The turnbuckle was turned to break or release friction at the shaft rotor to regulate the rotor speed.
- Forces F1, F2, and the rotor speed were recorded only if the system was in steady state.
- The rotor speed was regulated for a lower speed by turning down the turnbuckle for more friction until the rotor finally stopped rotating.

3. Theory

3.1 Wind turbine efficiency

Figure 6 presents a free body diagram of torque acting on the pulley. According to Newton's first law of motion, in the steady state the relative torque must be zero and then the shaft torque (T_{shaft}) can be determined from this equation:

$$T_{shaft} = (F_1 - F_2)R_p \tag{1}$$

where F1 and F2 are forces on both ends of the spring balances, and R_p is the radius of the pulley. The shaft torque leads to computation of the power coefficient (C_p) (Manwell, Mcgowan, & Rogers, 2009) as follows:

$$C_p = \frac{P_t}{P_w} = \frac{T_{shaft}\Omega}{0.5\rho A u^3} \tag{2}$$

where P_t is the wind turbine power, P_w is the wind power, Ω is an angular velocity of the rotor given by $\Omega = 2\pi N/60$, where N is the rotor speed (rpm), ρ is the density of air , A is the rotor swept area, and u is the speed of the wind. C_p is typically plotted against the tip-speed ratio (λ), which is calculated by $\lambda = \Omega R/u$ where R is radius of the rotor. However, the wind turbine efficiency is equal to $C_p \times 100\%$.

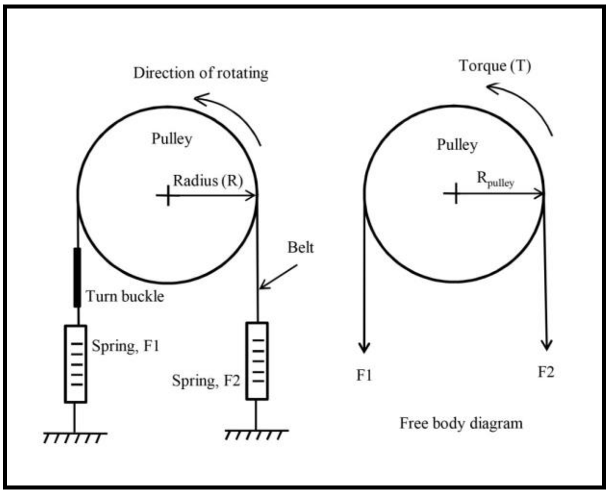

Figure 6. Free body diagram.

3.2 Rotor speed

The rotor should be operated at the optimal tip-speed ratio (λ_{opt}) in order to maintain the maximum efficiency at all times. This parameter is called the designed rotor speed (Ω_d) which can be determined by

$$\Omega_d = \frac{\lambda_{opt} u_d}{R} \tag{3}$$

where u_d is the designed wind velocity that can be deduced from the local wind statistic to give a maximum wind power possible ($P_{wd,max}$) (Figure 7b). Wind power density can be calculated by $P_{wd} = 0.5\rho A u^3 p(u)$, where p(u) is wind velocity probability distribution. This study used the Weibull function for p(u) (Dahbri, Benatiallah, & Sellam, 2013; Sridech, 2013) which can be represented by

$$p(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left\{-\left(\frac{u}{c}\right)^k\right\} \tag{4}$$

where k and c are the shape and scale parameters, respectively, and both of which depend on the wind statistics for a location, and u is the wind velocity.

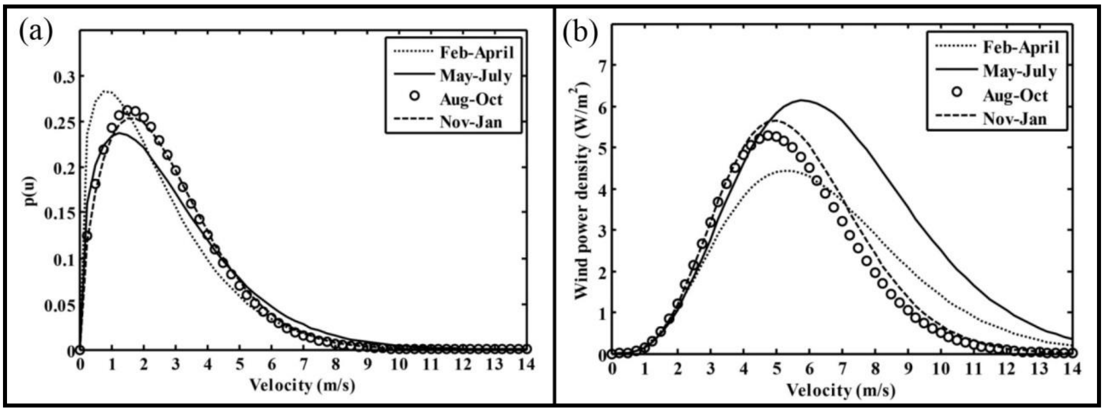

Figure 7. Weibull distribution
(a) Wind velocity probability distribution (b) Wind power density distribution.

3.3 Annual energy production

Annual energy production (AEP) can be investigated in 2 aspects, namely using wind velocity probability distribution for all year long or using wind velocity probability distribution for seasonal periods (Sridech, 2013). This study applied wind velocity probability distribution for seasonal periods in the Nakhon Ratchasima Province, from Exell (1981), whereby the k and c parameters were presented by grouping them into four three-month periods: February-April; May-July; August-October; and November-January. According to the k and c parameters in the Nakhon Ratchasima Province of Thailand (Exell, 1981) (Table 1), the wind velocity probability distribution for seasonal period (seasonal p(u) curve) can be shown in Figure 7a. It should be noted that when integrating the p(u) curve along the bin of wind velocity, the probability must be equal to 1.0 or 100%. Wind power density per unit area can be plotted (Figure 7b). The seasonal work period (W_P) can be determined as

$$W_p = H\int_u p(u)P_t du \tag{5}$$

Table 1. Scale and shape parameters (Exell, 1981).

Parameters	Feb-Apr	May-Jul	Aug-Oct	Nov-Jan
k	1.3	1.4	1.6	1.6
c	2.6	3.1	2.9	3
H (hr.)	2136	2208	2208	2208

H is the numbers of hour for a seasonal period, P_t is the wind turbine power which is $P_t = T_{shaft} \cdot \Omega$ and du is the bin difference. AEP is the summation of all seasonal period work along the year (annual energy production) as follows:

$$AEP = \sum_{i=1}^{n} W_{p,i} \tag{6}$$

where n is the total seasonal periods in a year.

4. Results and Discussion

4.1 Efficiency of the DTSW model

Two models (4-blade and 6-blade DTSW models) were examined with pitch angles (**β**) of 5, 10, 15, and 20 degrees by tow testing at a constant speed of 5.6 m/s. The first results present the power coefficient (C_p) or efficiency ($C_p \times 100\%$) of the two DTSW models (Figures 8a, 8b). It was apparent that the maximum efficiencies of the 4-blade and 6-blade DTSW models were about 17% and 25%, respectively, which was approximately at the optimum tip-speed ratio (λ) of 2.0-2.2. The optimum pitch angles of the 4-blade and 6-blade DTSW models were about 5 and 10 degrees, respectively. They were quite different perhaps because of the difference in the blade profile of the rotors which affected the angle of attacks differently, hence the aerodynamic loads. It

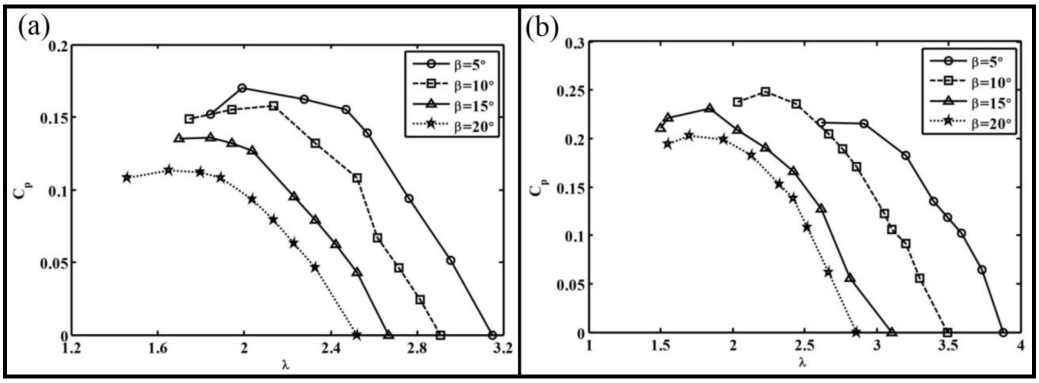

Figure 8. Power coefficient
(a) 4-blade DTSW model (b) 6-blade DTSW model.

can also be seen from Figures 8a and 8b that at the left sides of the $C_p-\lambda$ curves (after the peak point), which were the state for very low rotor speeds, the C_p data were not presented. This was because these states were operated at very high angles of attack where stall phenomenon prevailed (Choudhry, Arjomandi, & Kelso, 2016; Larsen, Nielsen, & Krenk, 2007; Qing'an, Yasunari, Takao, Junsuke, & Yusuke, 2016). The rotor could not produce enough torque to rotate so the C_p data could not be measured. A similar result was reported by Thepwong (2013).

4.2 Annual energy production

The $C_p-\lambda$ curves of both models are presented in Figures 8a, 8b. These curves led to an AEP estimation coupled with the Weinbull function as shown in equation (4). The AEPs of this study were estimated at the designed rotor speed (Ω_d) which depends on wind statistics and the optimal tip-speed ratio (λ_{opt}) which was known by the $C_p-\lambda$ curve. Then, both parameters were put into equation (3) to determine Ω_d. For the Nakhon Ratchasima Province of Thailand, the designed wind velocity (u_d) was about 5.0-6.0 m/s, since these velocities gave maximum wind power densities (Figure 7b). Actually, the wind velocity (u) can change at all times throughout the seasonal periods of the whole year. Therefore, the tip-speed ratio (λ) should also change following the equation $\lambda=\Omega_d R/u$. At the same time, the wind turbine power (p_t) in equation (5), depends on the wind velocity (u) and wind turbine efficiency ($C_p \times 100\%$) following equation (2). The seasonal work period can be determined by integration as shown in equation (3) and then the AEP can be determined by the summation of all seasonal work periods as shown in equation (6). The AEP results of both models are shown in Table 2 and in Figures 9a, 9b. It was apparent that the 6-blade DTSW model at β=10 degrees presented the

Table 2. Results of the seasonal work period and AEP.

Models	β ($^\circ$)	Work period (W-hr)				AEP (W-hr)
		Feb-Apr	May-Jul	Aug-Oct	Nov-Jan	
4-Blade DTSW model	5	4316	6290	4652	5155	20413
	10	4108	5970	4446	4920	19444
	15	3807	5501	4137	4561	18007
	20	3158	4611	3373	3740	14882
6-Blade DTSW model	5	5095	7298	5700	6265	24358
	10	8147	12314	7941	8934	37336
	15	8088	12302	7697	8671	36759
	20	6298	9271	6540	7267	29376

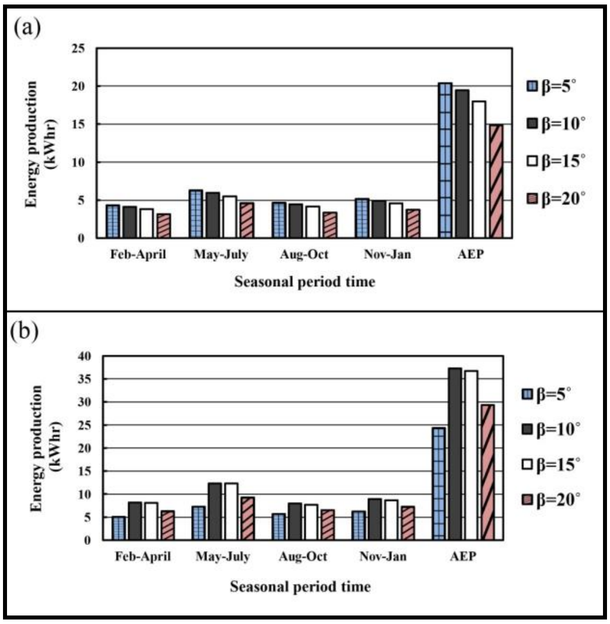

Figure 9. Seasonal work period and AEP
(a) 4-blade DTSW model (b) 6-blade DTSW model.

maximum AEP of 37.3 kW-hr and the 4-blade DTSW model showed the maximum AEP of 20.4 kW-hr at β=5 degrees. Furthermore, the May-July period gives the most seasonal work period (W_P) because this period presents higher wind velocity from the south-west monsoon phenomenon.

5. Conclusions

The 1-m radii downwind Thai sail windmills were investigated to determine the optimal pitch angles for maximum AEP. The 6-blade DTSW model gave better efficiency than the 4-blade DTSW model (25% vs. 17%). The optimum pitch angle of the 6-blade DTSW model was 10 degrees giving the maximum AEP of 37.3 kW-hr, while that of the 4-blade DTSW model was only 20.4 kW-hr at the optimum pitch angle of 5 degrees. The 6-blade DTSW model gives 83% more AEP than the 4-blade DTSW model for the wind velocity statistics in the Nakhon Ratchasima Province of Thailand.

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