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Effect of some design parameters on the performance of a Giromill vertical axis wind turbine

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Giromill;
Turbine performance;
Power coefficient

Abstract This paper describes the effect of some design parameters on the performance of a Giromill vertical axis wind turbine. A Giromill wind turbine has been designed, manufactured and tested. The turbine performance has been investigated with varying the design parameters such as, pitch angle, number of blades, airfoil type, turbine radius and its chord length. Then, the results were used for the comparison between the performance achieved while changing the design parameters.

Vast number of experiments have been performed with changing the above mentioned parameters. The effect of each parameter on the power coefficient and torque coefficient has been studied and explanation of the results was also discussed. It has been found that the pitch angle, turbine radius and chord length have a significant effect on turbine power coefficient.

The maximum power coefficient obtained in this research was 25% using turbine radius of 40 cm, chord length 15 cm, pitch angle of 10°, airfoil type NACA 0024, and four blades (which is found to be the best configuration in this study). For the effect of pitch angle, the obtained maximum power coefficient is decreasing, this decrease in performance was due to increasing in the pitch angle above 10° and also due to decreasing it below this value showing the high effect of pitch angle. It was also noticed that, when decreasing the turbine radius to 20 cm at 0° pitch angle the maximum power coefficient is much decreased. Moreover, decreasing the chord length to 12 cm at 10° pitch angle

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decreases the maximum power coefficient significantly, which again show the high effect of turbine radius and chord length. In order to compare the effect of airfoil type; the blades with NACA 4420 were used compared to NACA 0024 at the same above parameters of turbine radius 40 cm, chord length 15 cm, pitch angle of 10° and four blades. The maximum power coefficient obtained was 15%. Finally, the effect of the number of blades have been investigated using two, three and four blades at 0° pitch angle and the same other above parameters of turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024. The obtained maximum power coefficients were decreased significantly when decreasing the number of blades from four to two blades.

1. Introduction

The vertical axis wind turbines have many advantages over the horizontal wind turbines such as, the rotor shaft is placed vertically and can be located near the ground. The generator and the gearbox are placed near the ground. There is no need for a tower. Also, the turbine does not need to be pointed into the wind. This makes maintenance of the wind turbine quite easy. Also, the vertical axis wind turbine is quite cost effective.

They can be placed on hilltops, on ridgelines and on the top of buildings and in any areas where the force of the wind is more near the ground. Since they are placed lower, they can be used where tall devices are not allowed by the law. The main advantage of a vertical axis wind turbine, however, is that it turns in any direction with the wind; so, they do not need the yaw mechanism that is required in the horizontal axis design. As a result, the use of the vertical axis wind turbine may be efficient; although of having some disadvantages such as, they cannot cover a large area of wind. They are not very efficient with regards to extraction of energy because they operate near the ground where the air flow is turbulent.

An example of the design of Giromill wind turbine was previously carried out and the analyses of some design parameters was explained by Solum et al. [1]. The designed wind turbine was a three bladed 12 kW H-rotor with tapered NACA 0018 wing sections. It is connected to the rotating shaft through airfoiled struts with a C_p of about 0.35. Also, the experimental results for this turbine were introduced and studied by Deglaire et al. [2], the turbine performance was investigated in highly turbulent wind conditions and it was found that it is reacting fairly well with respect to these conditions.

Theoretical analysis and computational modeling was previously studied by Gyulai and Bej [3] and by Cooper and Kennedy [4] to predict the relation between the tip speed ratio and the power coefficient of the turbine. They developed a mathematical model for calculation of the performance and compared the results with the experimental results. Gyulai and Bej used some experimental results to adjust their model. Cooper and Kennedy, upon comparing the experimental results with multiple stream tube analysis, they found a fair agreement. Many other studies were carried out to facilitate the theoretical analysis and the performance predications of the vertical wind turbine such as, the study of the post-stall airfoil performance characteristics by Tangler and David Kocurek [5].

An excellent agreement was found between predicted rotor power and the measured ones. A study of the accuracy of different mathematical models which predict the performance of the turbine was carried out by Paraschivoiu et al. [6] through the comparison of the different model results such as, the Momentum model, the Double-Multiple stream tube model, Stochastic model, Viscous model and Dynamic-Stall model with experimental data.

An experimental and theoretical study of a prototype was performed for a 2.5 kW turbine using wind tunnel experimental data and CFD analysis by Tullis et al. [7], in which power curves have been developed at different wind speeds. The maximum power coefficient obtained was 0.28 for this prototype.

The performance of a Giromill with active blade control was previously measured and the control of pitch angle to improve the power coefficient was also studied by Hwang et al. [8]. It was found that the maximum power generated was at pitch angle 80 and phase angle 0°.

Paraschivoiu et al. [9] also studied the optimal variation of the blades' pitch angle of an H-Darrieus wind turbine that maximizes its torque at given operational conditions. They found that the optimized variable pitch leads to an improvement in C_p compared to 0° pitch angle of about 21% at wind speed of 7.3 m/s and turbine speed 125 rpm. At higher wind speeds (above 9 m/s) it results in a decrease of the turbine power. Three modifications for variable pitch control to improve the performance of the turbine were studied by Staelens et al. [10]. They examined the performance of a VAWT when the local angle of attack is kept just below the stall value throughout its cycle of rotation. This is accomplished by adjusting the local geometric angle of attack of the blade. This modification results in a very significant increase in the power output for wind speeds above 10 m/s. However, this modification requires sharp changes (jumps) in the local angle of attack making it physically and mechanically impossible to realize. They replaced the local geometric angle of attack by the local profile stall angle, obtained in the same manner as before.

As a consequence, this modification eliminates the two jumps in the local effective angle of attack curve but at the cost of a slight decrease in power output. Moreover, it also renders the angle of attack correction function which may be practically difficult to implement and result in an early fatigue. A remedy for this limitation is to introduce a smooth and continuous variation in the local angle of attack correction. Finally, he overcomes the limitation of the second modification by ensuring a continuous variation in the local angle of attack correction during the rotation cycle through the use of a sinusoidal function. The amplitude of the sinusoidal function was set equal to the maximum difference between the local geometric angle of attack and the blade static-stall angle. Although the power output obtained by using this modification is less than the two preceding modifications, it has the inherent advantage of being practically feasible.

Nomenclature

A	turbine swept area, m^2
c	chord length, m
F	force, N
l	blades length, m
P	power, W
r	turbine radius, m
T	torque, N m
v	wind velocity, m/s
v_{rel}	blade relative velocity, m/s
a	airfoil type
n	number of blades
C_d	drag coefficient
C_l	lift coefficient
C_p	power coefficient $= P/(0.5 \times \rho \times A \times v^3)$
C_t	torque coefficient $= T/(0.5 \times \rho \times r \times A \times v^2)$

Greek letters

ρ	density, kg/m^3
ω	rotational speed, rad/s
λ	tip speed ratio
γ	pitch angle, degrees
θ	azimuth angle, degrees
α	angle of attack, degrees

N.B. refer to Fig. 2 for an explanation of the above angles.

The effect of some design parameters such as, pitch angle and airfoil type has been previously introduced with some experimental data for comparison and analysis. Kinloch Kirke [11] studied ways for self starting of the turbine, performance prediction and the different parameters of airfoil which affect the performance.

No studies were carried out to determine the effect of different parameters variation such as, number of blades, pitch angle, turbine radius, chord length and airfoil type, and to determine the optimum variation. Accordingly, this paper aims at studying the effect of changing the design parameters on the performance of the Giromill vertical axis wind turbine with fixed pitch angle variation (coefficient of performance, tip speed ratio and torque coefficient). Also, to determine the variation which will result in the best performance based on the different performance parameters.

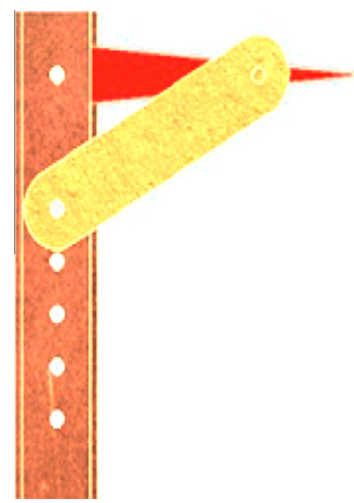

Figure 1a $\gamma = 0$.

2. Experimental setup and procedure

2.1. Wind turbine design

The used Giromill wind turbine model has the following components and parameters:

Shaft: The shaft is a solid steel shaft with a diameter of 30 mm as shown in Figs. 3a and b.

Blades: Three different NACA airfoil types were used. The material used was "Ayos" wood. The types are as follows: NACA 0024, NACA 4420 and NACA 4520 with chord lengths (8 cm, 12 cm, 15 cm) for each airfoil type with span length of 70 cm.

Caps: They were used to fix the blade from its upper and lower ends to the main links that are connected in turn to the disk. They were made from sheet metals taking the shape of the corresponding blades as shown in Fig. 3b.

Main links: Steel link were mainly used to transmit power from the blades to the disk and consequently to the shaft. Five holes were drilled in the link responsible for specifying the pitch angle as shown in Figs. 3a and b.

Auxiliary links: Steel link was used to change the pitch angle, this link has two holes one to fix it on the cap and the other matched with one of the five holes for the main link to change the pitch angle, as shown in Figs. 1a, b and 2.

Disks: Two Artelon – 10 mm thick and 20 cm diameter – disks were used to transmit the power from the main links to the shaft by means of friction. They were fixed to the shaft as shown in Fig. 3b.

Rings: Used to protect Artelon disks from being worn out as shown in Fig. 3b.

Glands: Two Aluminum glands were keyed to the shaft by means of a (8 mm) diameter clearance bolt as shown in Fig. 3b.

Pulley: A grooved Aluminum pulley was used to transmit the exerted force on the rope which is in contact with the pulley as shown in Fig. 3b. The exerted force on the rope here acts as the applied load on the turbine.

As the load increases the turbine slows down according to the following equations: $P = T \times \omega$, $T = (F_1 - F_2) \times r$, where 1 donates for one rod and 2 for the other.

Flanged bearing: Two square flanged ball bearings were used to fix the turbine to the test rig with 20 mm inner diameter.

2.2. Experimental setup

The used wind tunnel in this experiment consists of the following components:

(a) *Blower:* Double suction centrifugal blower was used with a power of 40 HP.

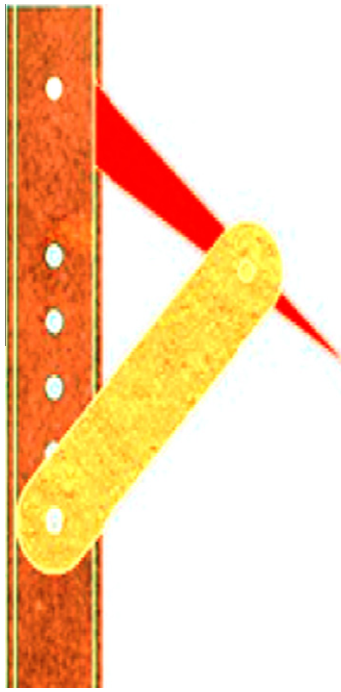

Figure 1b $\gamma = 40$.

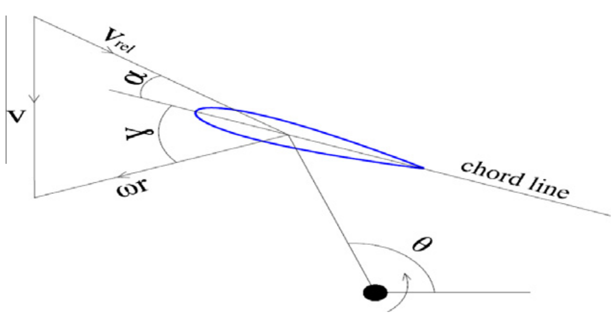

Figure 2 Schematic diagram showing γ, α and θ angles.

(b) *Wind tunnel sections:* A 985 cm length tunnel made from metal sheets delivering air flow from the blower to the turbine under test as shown in Fig. 4.

The tunnel is divided into four main sections: the first section consists of successive square shaped cross sectional area (80 cm × 80 cm) of length 100 cm each. The second section is increasing the cross sectional area from 6400 cm^2 to 22,500 cm^2 through a diffuser section. A tunnel with 205 cm length is the third section which acts as a damper for the flow to decrease the amount of vibrations on the tunnel. The fourth section is a (1 m × 1 m) cross sectional area which is the outlet to the turbine under test.

Test section: A steel frame was used to fix the turbine in front of the wind tunnel inlet as shown in Fig. 4.

Air speed: Air speed used in this experiment was 8 m/s.

2.3. Instrumentation

Digital tachometer: To measure the turbine speed (rpm) with an accuracy of ±1%.

Vane anemometer: The vane anemometer is an instrument that is used to measure wind speed (air speed), it can also measure wind direction. The outlet of the wind tunnel outlet was divided into nine sections in order to measure the wind speed in each section to obtain the average wind speed at the tunnel outlet with an accuracy of ±1.5%.

Force gauges: It measured the tension in the rope attached to the pulley with an accuracy of ±1.5%.

3. Results and discussions

The following curves describe the comparisons of the performance of some variations resulting from changing the design parameters (airfoil type, chord length, turbine diameter, number of blades and pitch angle).

3.1. Effect of pitch angle on C_p, C_t and λ

As shown in Figs. 6–9, these curves were obtained from changing the pitch angle (0°, 10°, 20°, 30°, 40°, 50°, 60° and -10°) with different variations of number of blades, turbine radii, chord lengths and airfoil types.

We can see from Figs. 6–8 that the pitch angle of 10° gives the highest performance regarding C_p, C_t and λ ($C_p = 25\%$ at $\lambda = 1.3$ and $C_t \approx 0.2$ at $\lambda = 1$). It can be concluded from the below figures that the performance decrease significantly (results in lower C_p and C_t both at a lower λ) with increasing the pitch angle above 10°. The performance also decreases when decreasing the pitch angle below 10°, which shows that pitch angle has a significant effect on the performance. The same comparison of the effect of pitch angle is also shown in Figs. 7 and 9 but using a different airfoil type and we get the same above conclusions.

Figure 3a Turbine and test rig photo.

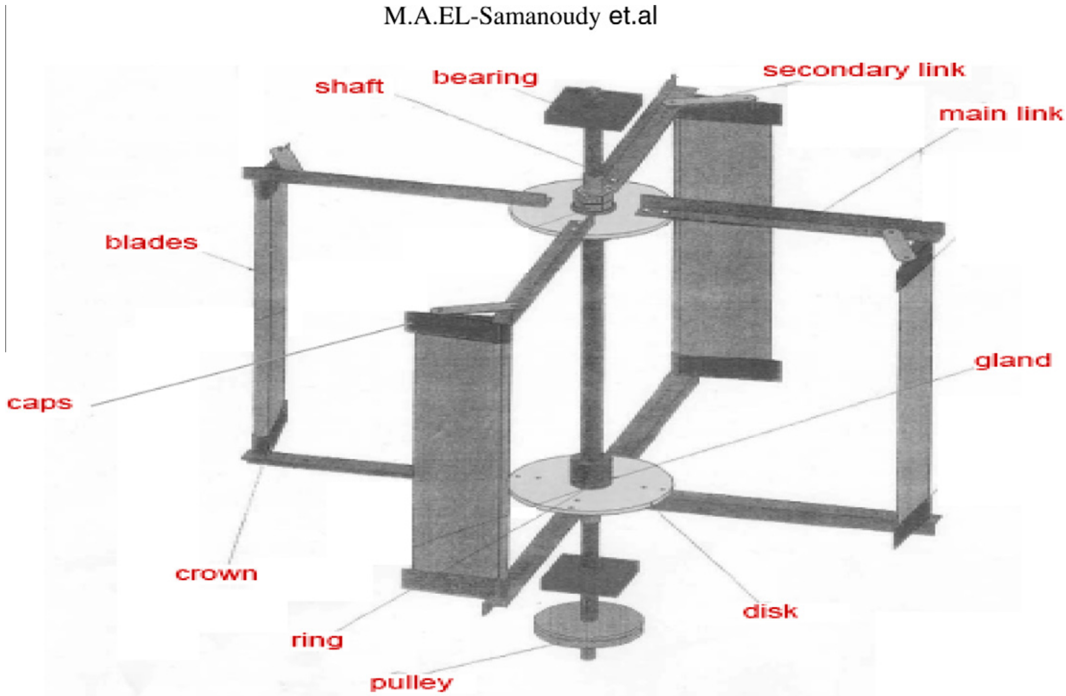

Figure 3b Turbine diagram.

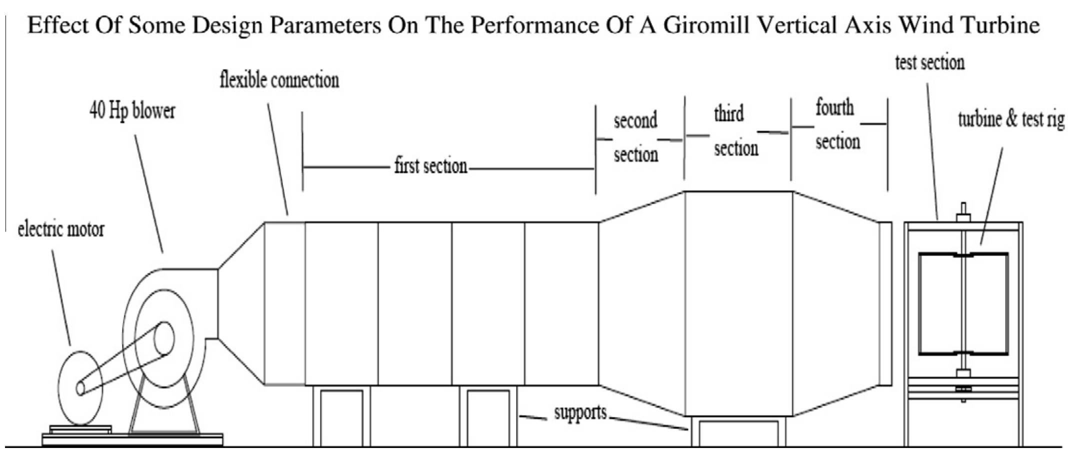

Figure 4 Test rig and wind tunnel arrangement.

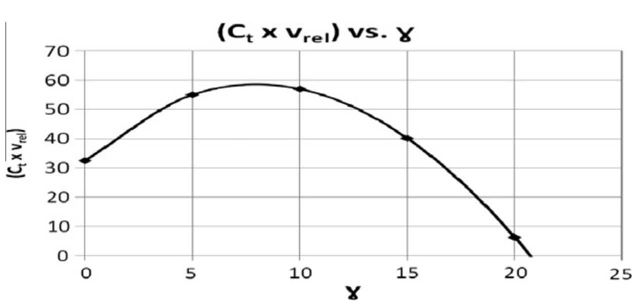

Figure 5 $(C_t \times v_{rel})$ vs. γ for a four symmetrical airfoil blades at $\lambda = 1.4$ using approximation for C_l and C_d values.

This can be explained through the following formulas which describes the changes of C_p with α, γ, C_l, C_d and λ

$$C_p = \frac{1}{2} C_t \rho c l v_{rel}^2 r \omega n \Big/ \frac{1}{2} \rho A v^3 = \frac{1}{2} C_t c v_{rel}^2 \lambda n / r v^2 \tag{1}$$

$$C_t = C_l \sin\alpha - C_d \cos\alpha \tag{2}$$

$$\begin{aligned} v_{rel} &= \sqrt{((v\sin\theta)^2 + (\omega r + v\cos\theta)^2)} \\ &= v\sqrt{\sin^2\theta + (\lambda + \cos\theta)^2)} \end{aligned} \tag{3}$$

C_l and C_d are functions of α, Re (Reynolds number) and the particular airfoil section:

$$\begin{aligned} \alpha &= \tan^{-1}(v\sin\theta/(\omega r + v\cos\theta)) - \gamma \\ &= \tan^{-1}(\sin\theta/(\lambda + \cos\theta)) - \gamma \end{aligned} \tag{4}$$

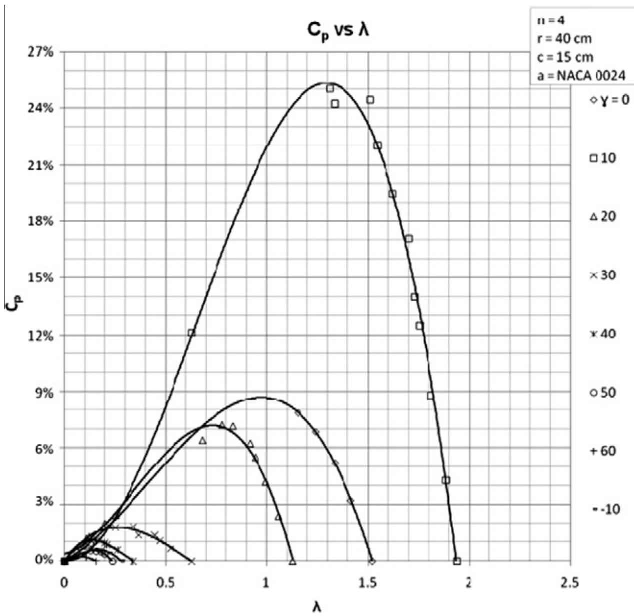

Figure 6 C_p vs. λ at different pitch angles using four blades, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024.

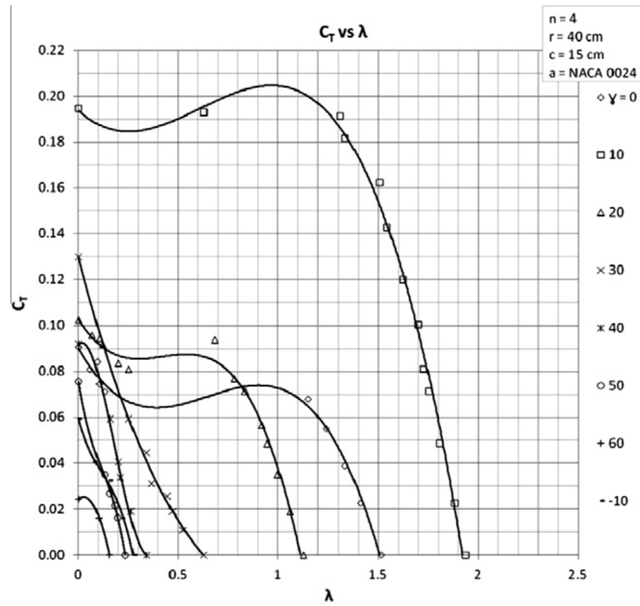

Figure 8 C_t vs. λ at different pitch angles using four blades, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024.

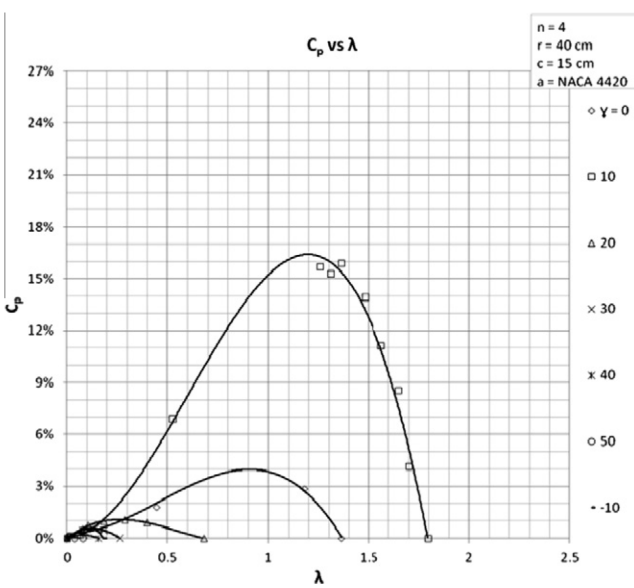

Figure 7 C_p vs. λ at different pitch angles using four blades, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 4420.

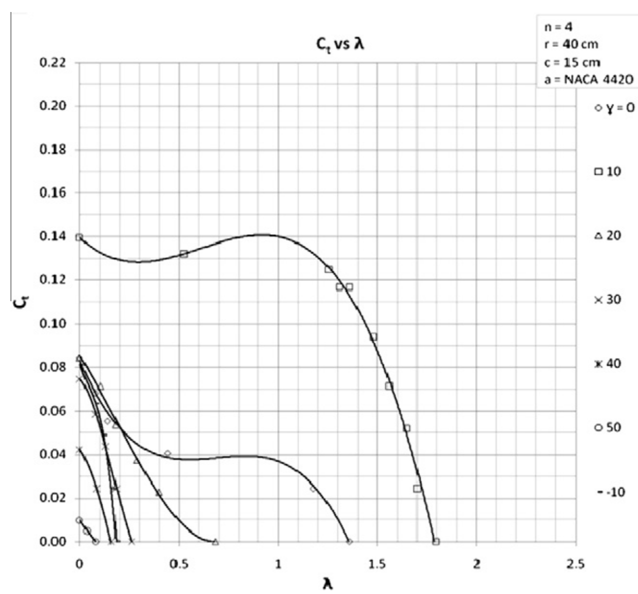

Figure 9 C_t vs. λ at different pitch angles using four blades, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 4420.

$$C_l = (1 + 0.05\ (\%\ \text{camber}))\sin 2\alpha\ (\text{as an approximation [11]}) \tag{5}$$

$$C_d = (0.9 + 0.025\ (\%\ \text{camber})) \times (1.5\sin^3\alpha + 0.5\sin\alpha + 0.05\ (\%\ \text{camber}))\ (\text{as an approximation [11]}) \tag{6}$$

We can see from Eq (1) that the relation between C_p and λ depends on the term $(C_t \times v_{rel}^2)$. By plotting the relation between $(C_t \times v_{rel}^2)$ (for the upwind blades) and γ at different values of λ using the above formulas we will find that the maximum value of $(C_t \times v_{rel}^2)$ and accordingly C_p occurs at about 10° as shown in Fig. 5. There are deviations in the actual values from the calculated values because of the approximation of C_l and C_d values and due to changes in Re number and the unsteady effects of changing α rapidly which have an effect on increasing the stall angle and maximum values of C_l as observed by Klimas.

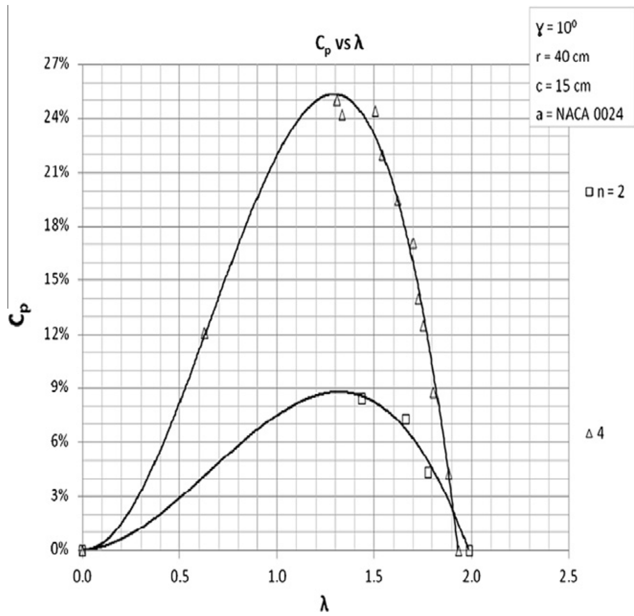

Figure 10 C_p vs. λ using different number of blades at pitch angle 10°, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024.

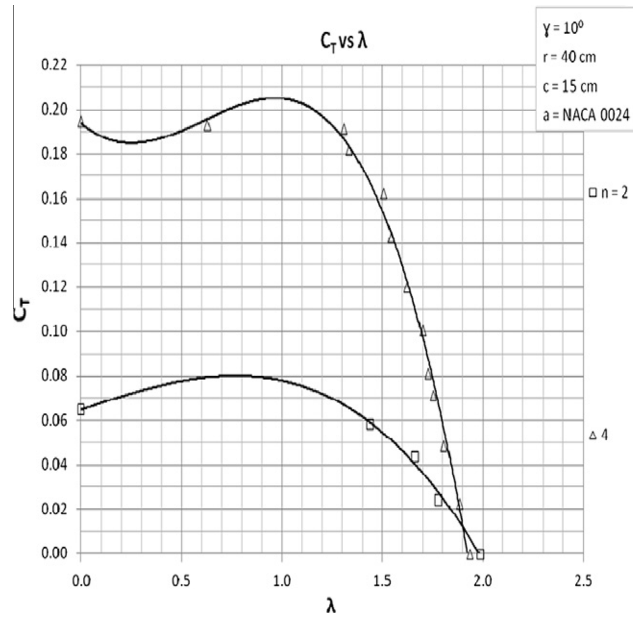

Figure 12 C_t vs. λ using different number of blades at pitch angle 10°, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024.

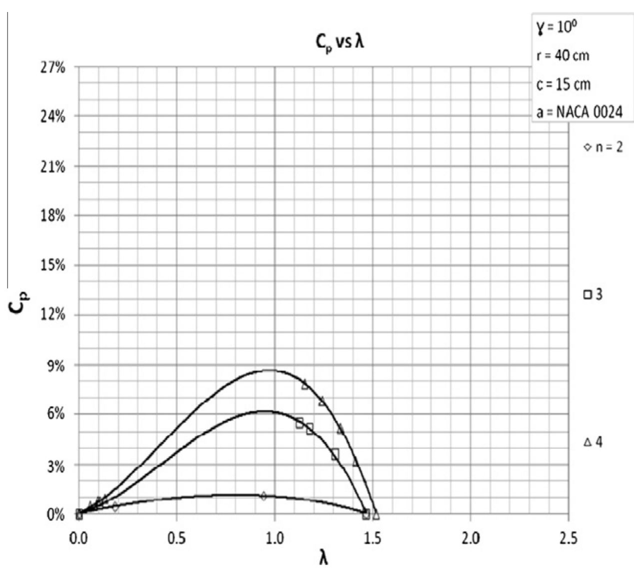

Figure 11 C_p vs. λ using different number of blades at pitch angle 0°, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024.

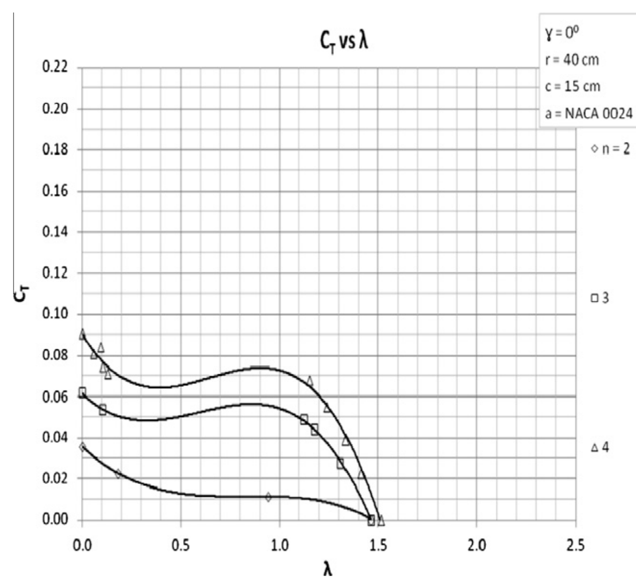

Figure 13 C_t vs. λ using different number of blades at pitch angle 0°, turbine radius 40 cm, chord length 15 cm and airfoil type NACA 0024.

3.2. Effect of number of blades on C_p, C_t and λ

As shown in Figs. 10–13, these curves were obtained from changing the number of blades (2, 3 and 4 blades) with different variations of pitch angles, turbine radii, chord lengths and airfoil types.

We can see from Figs. 10 and 12 that using four blades results in the highest performance regarding C_p, C_t and λ (C_p = 25% at λ = 1.3 and C_t = 0.205 at λ = 1) and when decreasing the number of blades to two blades the performance was much decreased. It can be seen from Figs. 11 and 13 that when decreasing the number of blades to three blades there is a small decrease in performance. So, we can conclude that increase in the number of blades from two to four blades has a significant effect in increasing the performance while increasing the number of blades from three to four has a small increase in performance.

This is expected as the higher number of blades results in higher torque at the same speed.

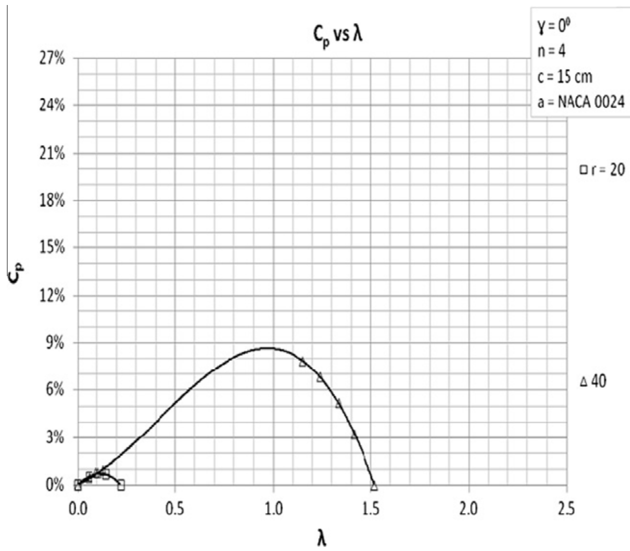

Figure 14 C_p vs. λ using different turbine radius at pitch angle 0°, four blades, chord length 15 cm and airfoil type NACA 0024.

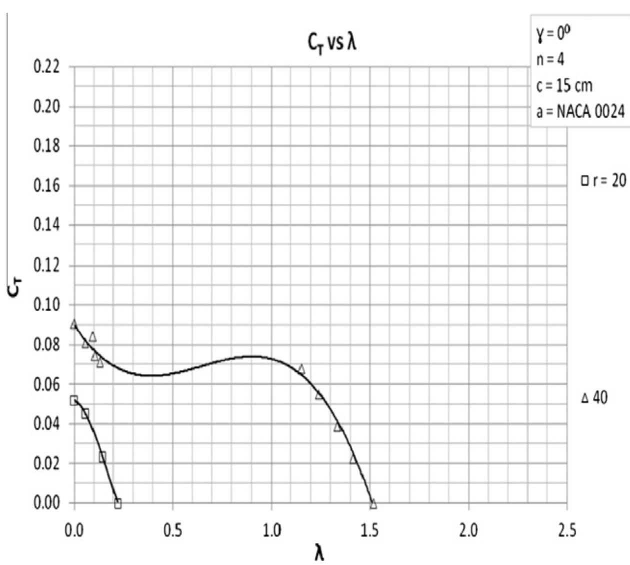

Figure 15 C_t vs. λ using different turbine radius at pitch angle 0°, four blades, chord length 15 cm and airfoil type NACA 0024.

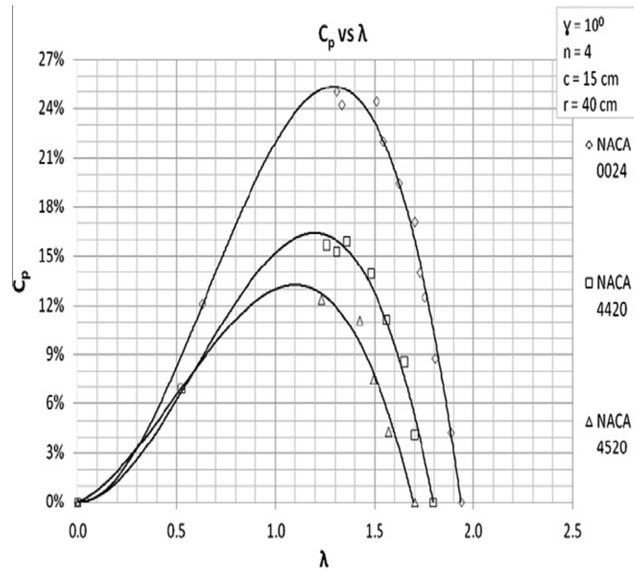

Figure 16 C_p vs. λ using different airfoil types at pitch angle 10°, using four blades, chord length 15 cm and turbine radius 40 cm.

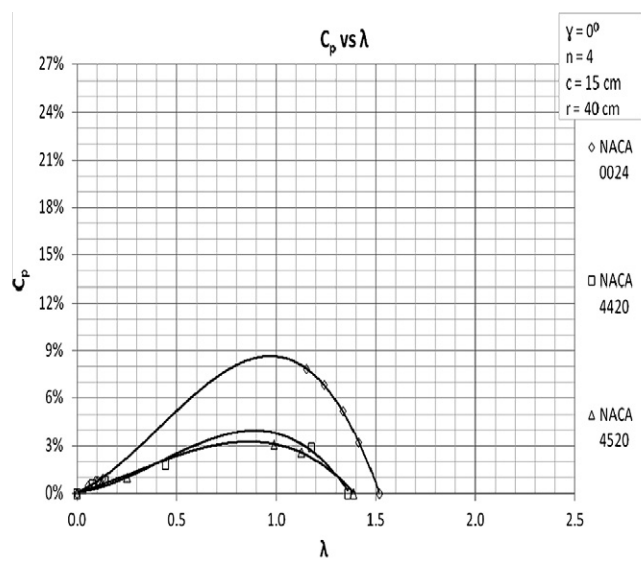

Figure 17 C_p vs. λ using different airfoil types at pitch angle 0°, using four blades, chord length 15 cm and turbine radius 40 cm.

3.3. Effect of turbine radius on C_p, C_t and λ

As shown in Figs. 14 and 15, these curves were obtained from changing the turbine radius (20 cm and 40 cm) with different variations of number of blades, pitch angles, chord lengths and airfoil types.

We can see from Figs. 14 and 15 that; when we decrease the turbine radius from 40 cm to 20 cm, the performance was much decreased showing the significant effect of changing the turbine radius.

The lower performance at the lower radius is due to the effect of the shaft and the downwind blades on the flow past the blades which decrease the velocity of the wind past the upwind blades.

3.4. Effect of airfoil type on C_p, C_t and λ

As shown in Figs. 16–19, these curves were obtained from changing the airfoil type (NACA 0024, NACA 4420 and NACA 4520) with different variations of number of blades, turbine radii, chord lengths and pitch angles.

As shown in Figs. 16 and 18, the symmetrical airfoil NACA 0024 results in higher performance regarding C_p, C_t and λ; the airfoil NACA 0024 gives higher C_p compared to NACA 4420 and NACA 4520. There is a significant improvement in performance results from using NACA 0024 airfoil instead of NACA 4520, while there is a much lower improvement in performance results from using NACA 4420 airfoil instead of NACA 4520.

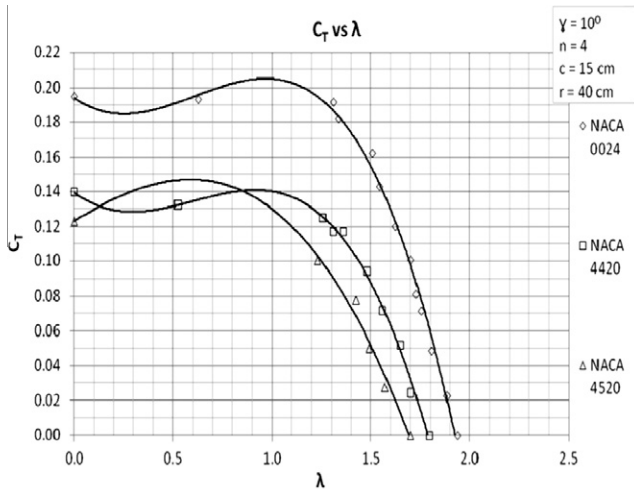

Figure 18 C_t vs. λ using different airfoil types at pitch angle 10°, using four blades, chord length 15 cm and turbine radius 40 cm.

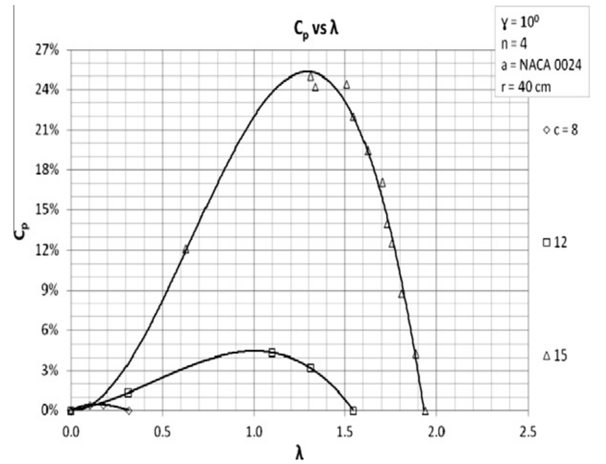

Figure 20 C_p vs. λ at different chord lengths at pitch angle 10°, using four blades, airfoil type NACA 0024 and turbine radius 40 cm.

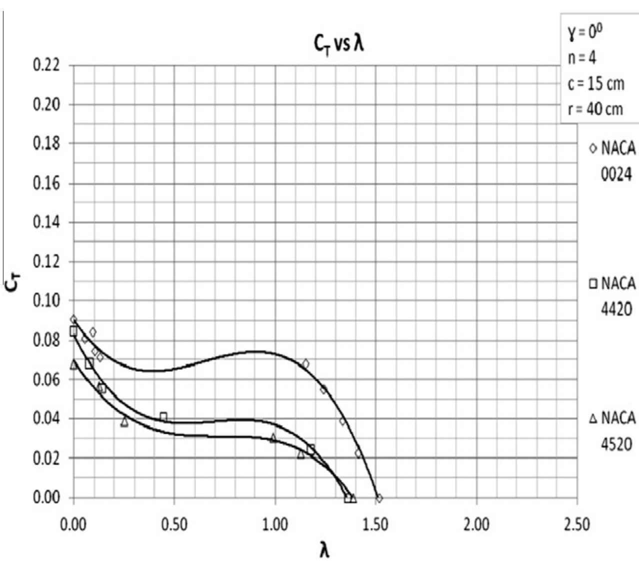

Figure 19 C_t vs. λ using different airfoil types at pitch angle 0°, using four blades, chord length 15 cm and turbine radius 40 cm.

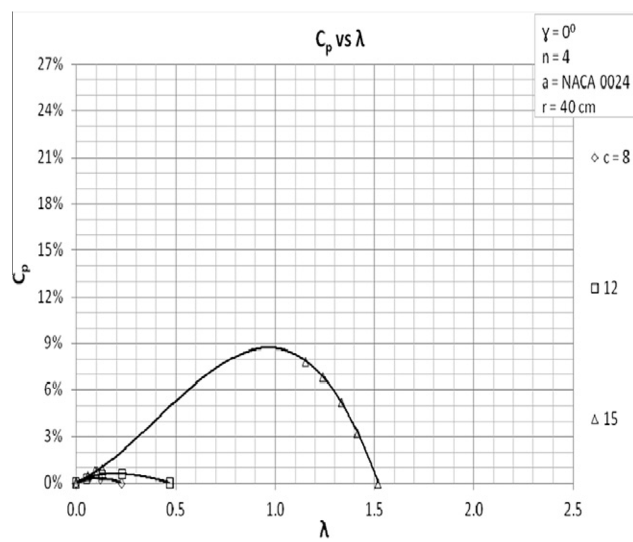

Figure 21 C_p vs. λ at different chord lengths at pitch angle 0°, using four blades, airfoil type NACA 0024 and turbine radius 40 cm.

The higher performance of the symmetrical airfoil is the result of the difference of the characteristics of the change of C_l and C_d with α (for example the cambered airfoils has positive values of C_l for certain range of negative α, while this is not the case with symmetrical airfoil which has negative C_l for all negative values of α. Also, cambered airfoils have higher C_d values compared with that of symmetrical airfoils at the same angle of attack).

3.5. Effect of chord length on C_p, C_t and λ

As shown in Figs. 20–23, these curves were obtained from changing the chord length (8 cm, 12 cm and 15 cm) with different variations of number of blades, turbine radii, pitch angles and airfoil types.

Figs. 20 and 22 show that increasing the chord length has a significant effect in increasing performance, while Figs. 21 and 23 give the same conclusion but at different pitch angle.

This can be explained due to the higher projected area which increases the aerodynamic force on the blades and due to the higher Re number which results in higher C_l values with increasing the chord length.

4. Comparison between experimental data and previously published works

A theoretical analysis was carried out by Whitten [12] by using approximation of lift and drag data of NACA 0012 blades [13], and a comparison of this theoretical analysis

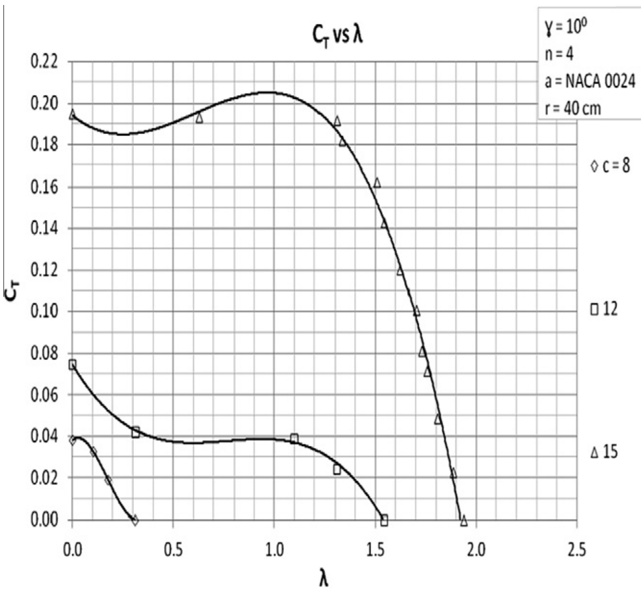

Figure 22 C_t vs. λ at different chord lengths at pitch angle 10°, using four blades, airfoil type NACA 0024 and turbine radius 40 cm.

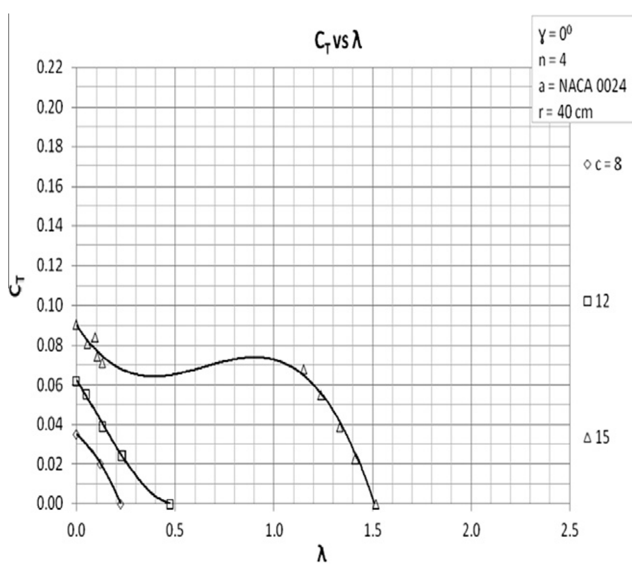

Figure 23 C_t vs. λ at different chord lengths at pitch angle 0°, using four blades, airfoil type NACA 0024 and turbine radius 40 cm.

and previous experimental data was also performed by Cooper and Kennedy [4].

The theoretical analysis and the results of the experimental data previously obtained by Cooper and Kennedy [4]; showed that the maximum power coefficient is about 0.25 for the model used.

It has been showed by Hwang et al. [8] that the best performance is achieved at pitch angle about 8° which is confirmed by the results obtained in this research.

It is also showed by Hwang et al. [8] that the improvement achieved by active pitch control over fixed pitch turbine is more with higher wind speeds.

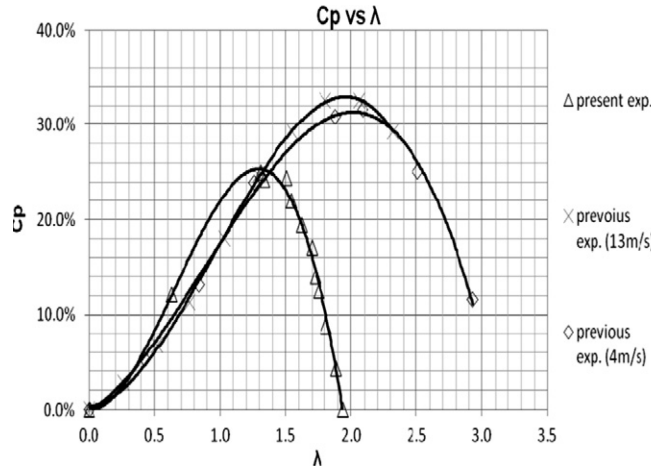

Figure 24 Comparison between present experimental results and previous results [8].

A comparison between the results obtained in the previously experimental results [8] and the results obtained in this research is shown in Fig. 24.

The parameters of the present and previous experiments in the above comparison are as follow:

Parameters	Present exp. (8 m/s)	Previous exp. (13 m/s) [8]	Previous exp. (4 m/s) [8]
Number of blades	4	4	4
Airfoil type	NACA 0024	NACA 0018	NACA 0018
Radius of rotor (m)	0.4	1.6	1.6
Span length of blades (m)	0.7	2	2
Chord length of blades (m)	0.15	0.45	0.45
Pitch angle (°)	10	8	8
Wind speed (m/s)	8	13	4

A fair agreement was found between previous experiments and the results of this research.

5. Conclusions

From the above results we can conclude the following:

(1) The pitch angle is an important parameter on the C_p, C_t and λ (the maximum values obtained at about 10°).
(2) The chord length has a significant effect on the C_p, C_t and λ (increasing the chord length increasing these values).
(3) The turbine radius has a remarkable effect on the C_p, C_t and λ (increasing turbine radius increases these values in the range of this study).
(4) There is noticeable increase in C_p, C_t and λ resulting from increasing the number of blades from two to four blades. Less increase in these values results from the increase in the number of blades from three to four blades.
(5) Symmetrical airfoil (NACA 0024) results in higher C_p, C_t and λ, and there is a little increase in these values resulting in changing airfoil type from NACA 4520 to NACA 4420.

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