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Effect of Shroud Components on the Performance of a Small Horizontal Axis Wind Turbine

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ABSTRACT

A small horizontal axis wind turbine has been tested experimentally to show the influence of shroud components on the turbine's overall performance. The reference case was the bare wind turbine. The different parts of the shroud are connecting ring, inducer, diffuser, and lens. The maximum power coefficient (C_p) of the used bare HAWT is 0.1969 (1st case). When the connecting ring was attached to the reference case (2nd case), the maximum C_p decreased to 0.1695. In the (3rd case) an inducer is attached to the connecting ring, maximum C_p increased to 0.2213, about 11% higher than the bare wind turbine. When adding a diffuser part to the inducer and the connecting ring (4th case), the performance increased to 0.347, which is improved by 36.2% compared to the third case and 43.26% to a bare wind turbine. In the (5th case) a lens was added to the diffuser outlet to construct a full shroud. For this construction, the best performance is obtained at C_p of 0.35. This case improved the performance by 43.74%, more than the bare turbine. To reduce the construction cost, in the (6th case), the inlet inducer is removed and the connecting ring with flanged diffuser assembly is examined, under the same working condition, the performance is reduced to 0.308. Although the performance, in this case, was lower than the case of a full shroud, it improved the performance over the bare turbine and the case of inducer-connecting ring assembly by 36.07% and 44.97% respectively.

Keywords: Diffuser-augmented wind turbine; Renewable energy; Shrouded wind turbine; Small horizontal axis wind turbine

1. INTRODUCTION

According to the Betz limit, a bare horizontal axis wind turbine cannot transform more than 0.593 of the wind energy into mechanical energy. This limitation is because the wind used has an area less than the swept area of the wind turbine and a certain amount of the kinetic energy of the wind must be rejected at the exit to enable the wind to flow through the wind stream tube. From these two points of reduced used wind area and rejected kinetic energy, all trials have been done to recover them and increase the Betz limit. In 1981 a shrouded wind turbine was proposed by Igra [1]. The shroud consists of an inducer to increase the swept wind area and a diffuser to decrease the rejected kinetic energy at the exit. The shroud was made of concrete which separates the exiting wind from the free wind with higher energy.

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This simple shroud caused wind blocking, as the free stream tried to return into the shroud. The first successful trial of this solid shroud was inserting different nozzles around the diffuser to inject free wind and pushing the weak exiting wind from the turbine to leave the diffuser. This method had limited success and increased the power extraction from the wind. A more successful idea was initiated by using a lens at the diffuser exit (flanged diffuser), Ohya et al.[2]. This lens works as a destroyer of the free outside wind energy near the shroud to let the exiting wind leave the turbine to flow outside the diffuser.

In order to compare the performance of a free wind turbine and a wind turbine attached with a diffuser Kosasih and Tondelli [3] used three different diffusers (straight diffuser, nozzle-diffuser, and brimmed diffuser) were implemented in the shroud geometry surrounding the turbine blades. The diffuser geometrical parameters such as diffuser lengths (L:D = 0.63 to 1.5) and flange heights (H:D = 0.0 to 0.2) have been investigated.

It is concluded that the diffuser shroud enhances the performance by 60.0 % but the nozzle-diffuser element enhances the performance by 63.0 % compared to the free turbine. Adding a brim to the diffuser also enhances the performance. Investigating the diffuser length (L:D) shows no effect on the power coefficient (C_p) but shifts the performance curve and the resulting optimum (C_p) to a high tip speed ratio (λ).

The effect of the shroud and ejector has been examined by Han et al. [4]. A horizontal-axis wind turbine with a shroud and ejector was designed to be used for low wind speed. Using the commercial software CFX the wind turbine performance was evaluated and it was concluded that the efficiency of the designed wind turbine increased to 66.0 – 73.0 % at low wind speed from 2.0 to 6.0 m/s. It was found the shroud and lobed ejector construction in the downstream side of the wind turbine reduced the pressure at the wind turbine outlet so that the turbine output power was increased by 240 % then the proposed wind turbine can be used in case of low wind speed.

To investigate the effect of winglet length and cant angle on a small horizontal-axis wind turbine performance Khaled et al. [5] performed a computational study using ANSYS Fluent commercial software at steady-state flow. A numerical study and optimization using Artificial Neural Network (ANN) were conducted for different designs of winglet by varying lengths and cant angles. The length of winglet was varied from 1.0 to 7.0 % of the wind turbine rotor radius with a cant angle from 15^o to 90^o. The power coefficient and thrust force coefficient were investigated for different winglets. The wind speed changed from 3.12 m/s to 12 m/s. It is concluded that the power and thrust coefficients in the case of turbine blades with winglets was enhanced. In the case of winglet length was 6.32 % and cant angle was 48.3^o the power coefficient and thrust coefficient increased by the same percentage of 8.787 %.

Kumar and Saha [6] proposed a shrouded-twin-rotor turbine design. The power coefficient of the proposed design exceeds the Betz-Joukowsky limit (59.3 %) [7] because the shroud increases the air mass flow rate. It is found that the proposed design is better than the single-rotor because the proposed configuration can run as turbine-turbine mode or turbine-fan mode which achieve maximum power coefficient.

Lipian et al. [8] compared the (C_p) of a rotor in different configurations: Shrouded and open, single and twin rotor systems. The effect of low Reynolds number flow on the performance is examined. It is shown that, while enhancing the turbine performance (up to a twofold increase), using a shroud increases the rotor load. Apply the second rotor may be a solution to that issue. Although the implementation of the second rotor provides a modest efficiency increase (11-13 % for the un-shrouded, 4-5 % for the shrouded turbine), it distributes the loads more evenly on turbines.

Riyanto et al. [9] investigated the performance of a horizontal wind turbine using a diffuser of two different geometries: without an inlet shroud (L:D = 0.25) and with an inlet shroud (L:D = 0.39). Low wind speed (1-5 m/s) from a wind tunnel is used to perform the test on the wind turbine. It is shown that the produced power increases by adding a diffuser. Implementation of the diffuser without an inlet shroud improves the power efficiency by up to 20.50 % while the diffuser with an inlet shroud increases the power efficiency by up to 41.10 %. It is concluded that attaching a diffuser to the turbine assembly improves the performance of wind turbines.

2-D flow around a ‘NACA 63 – 415’ airfoil ‘the typical wind-turbine-blade profile’ has been computationally investigated by Erkan et al. [10]. The flow mechanism and aerodynamic loads over the selected blade profile are examined to identify the optimum angle of attack. Reynolds numbers of $10^5 \leq Re \leq 3\times10^6$ are used for Simulations with angles of attack $0^o \leq \alpha \leq 20^o$. Two different turbulence models; the Spalart-Allmaras and the Shear-Stress Transport (SST) k-ω turbulence models were applied to solve the turbulent flow field and to compare between data obtained with different models. After validating the results it is concluded that the optimum angle of attack ‘α’ for this blade profile is 6^o for $Re \leq 10^6$ and 7^o for $Re \geq 1.6\times10^6$.

Siavash et al. [11] Developed a small wind turbine provided with a controllable nozzle diffuser duct or shroud. The shroud consists of a fixed ring and a two-piece flexible diffuser to alter the diffuser wall opening from 0^o to 180^o. The proposed mechanism is developed to control the speed up ratio (γ) and the drag forces acting on the turbine at high wind speed. The duct geometry is designed by CFD works. Depending on the experimental results it is concluded that a significant rise in power generation and rotor speed have been achieved by using the shrouded wind turbine. The enhancement ratio on average is 39.75 % for the case of a 180-degree diffuser wall opening, while the ratio is 28.5 % for the case of a complete diffuser-shrouded wind turbine. The rotor speed up ratio for the studied cases is 53 and 74 % respectively. Later on, Siavash et al. [12] presented a mathematical model to predict the power coefficient and speed up ratio effects on a shrouded wind turbine. In the proposed model, the pressure drop through the duct is considered and the velocity in the far-wake is different from the bare wind turbine. The mathematical model showed that a proper duct design of C_p = 0.93 can be obtained practically. For optimum condition it is concluded; that the static pressure difference between the duct outlet and the surrounding atmosphere should be about - 0.6, the duct exit area ratio (β) and duct efficiency (η_d) should be 0.45 and 0.85 respectively, and the speed up ratio should be 0.6 < γ < 1.7.

Leloudas et al. [13] performed a numerical simulation to optimize the shape of a diffuser-augmented for a 15 kW wind turbine. The axisymmetric RANS solver based on SST turbulence model has been applied for the simulation. It is showed that a shrouded design (SD1) achieving a mean velocity speed up ratio of 1.9, which is about 23 % greater than that of the baseline design, and reducing the surface drag by approximately 47 %. In the region downstream of the rotor plane the small thickness distribution of SD1 could be a critical point that affects the structure of a certain design. As a remedy, modification of the shroud profile (SD2) was designed by thickening SD1. The drag reduction was 45 % and the increase in the mean velocity speed up ratio was 21 %. A significant volume reduction, about 48 % and 41 % for SD1 and SD2 respectively, was achieved. It is concluded that the designs (SD1 and SD2) can provide high velocity accelerations, which result in a remarkable reduction in drag and volume.

As an attempt to study the dimpled surface blades effect on turbine performance Sedighi et al. [14] investigated numerically the performance of a horizontal axis wind turbine. Some spherical dimples are added to the suction sides of turbine blades. The incompressible (RANS) solver and k-ω Shear-Stress Transport (SST) turbulent model are applied. The influence of radius, location, and dimples number on the wind turbine aerodynamic performance has been examined. Blade pitch angle and wind speed effect is also examined on the best-dimpled blades. Implementing 150 dimples of r = 15, 25, 50, and 70 mm arranged in 3 rows at 20, 40, and 60 % chord-wise from the leading edge with dimple pitch distance P_d of 150, 200, 300, 400 mm. It is concluded that the dimple arrangement of r = 25 mm and pitch distance P_d = 200 mm could increase the generating torque by 16 %.

Experimental and numerical study were carried out by Eltayesh et al. [15] to investigate the impact of blade number on the power and thrust coefficients of a small horizontal axis wind turbine. Rotors with different number of blades, 3, 5, and 6 at different tip speed ratios were installed on wind turbine. A steady-RANS method and SST k-ω turbulence model numerical simulations were performed. It is concluded that the wind turbine performance could be enhanced by decreasing the number of blades. The wind turbine with 3-blades configuration has the best power coefficient with respect to 5 and 6 blades turbines, higher by around 2 and 4 % respectively.

To investigate the effect of different blade configurations on small-scale wind turbine performance, experimental and numerical study have been conducted by Mohamed et al. [16] using Ansys CFD software. A 3-D computational model of the rotor system is created and simulated by applying Realizable k-ε turbulent model to examine the performance of 4 types of blade configurations (NACA 0012 with Straight and Twisted blades, NACA 4418 with Straight and Twisted blades). Different wind speeds varying from 2 m/s to 8 m/s have been used to determine the (C_p) for different blade configurations with wind speed. It is shown that the numerical solution predicts the power produced by 15 % greater than the experimental results for all tested blade configurations. The most effective design of blades was untwisted blades with NACA 0012 which gave an average power coefficient of 0.41.

CFD and experimental approaches have been used by Alkhabbaz et al. [17] to analyze the effect of a compact diffuser on a small wind turbine aerodynamic behavior. An optimization approach was implemented to optimize the geometrical features of the shroud. It is found that the total length of the optimized shroud is shorter by 6 percent than the original configuration. In addition to that, the optimized shroud profile improved the wind speed by 1.58 % greater than the basic configuration at the same throat area. After investigating the bare and shrouded wind turbines, for two different cases; constant rotor speed and constant wind speed by CFD and experimental test. It was concluded that the shroud enhances the aerodynamic performance more than two-fold compared to the conventional turbine. The enhancement of the (C_p) obtained from the shrouded wind turbine was 66.4 % and 69.3 % based on CFD results and experimental test respectively compared to the basic one.

From this review there is no study that examined every individual component of the shroud and its effect on the horizontal axis wind turbine performance. Consequently, in this study, the effect of different parts of the shroud is investigated to evaluate its impact on the system performance compared to the bare turbine.

2. EXPERIMENTAL SETUP AND PROCEDURES

The most important parameters to investigate the performance of a small horizontal-axis wind turbine are the power coefficient (C_p) and the tip speed ratio (λ) [18].

The power coefficient (C_p) deals with the converting efficiency in the first stage, defined as the ratio of the actual captured mechanical power by blades to the available power in wind, and can be expressed as:

$$C_p = \frac{\text{mechanical power produced}}{\text{wind power into turbine}} = \frac{P_{m.out}}{P_{w.in}}$$

$$C_P = \frac{P_{m.out}}{0.5\ \rho\ A\ \bar{u}^3} = \frac{T\ \omega}{0.5\ \rho\ A\ \bar{u}^3} \qquad (1)$$

Where; $P_{m.out}$ is mechanical power produced, $P_{w.in}$ is wind power, T is torque, ω is the angular velocity of blades and $\bar{u}$ is the average wind speed.

$$T = F \times R \qquad \text{(N.m)} \qquad (2)$$

$$F = m \times g \qquad \text{(N)} \qquad (3)$$

$$\omega = \frac{2\pi N}{60} \qquad \text{(rad/s)} \qquad (4)$$

Where; F is the force, R is the radius of the wheel, m is the mass, g is the acceleration of gravity and N is the speed of rotation.

The tip speed ratio (λ) is an extremely important factor in wind turbine design, which is defined as the ratio of the tangential speed at the blade tip to the actual wind speed and expressed as:

$$\lambda = \frac{\omega\ R_b}{\bar{u}} = \frac{\omega\ (l+r)}{\bar{u}} \qquad (5)$$

Where; l is the length of the blade, r is the radius of the hub and R_b is the total blade length.

To investigate the shroud components that affect a small HAWT performance, the effect of every part, or combination of them, constructing the shroud has been examined. Different parts such as: connecting ring, inducer, non-flanged diffuser, and flanged diffuser have been attached to the bare wind turbine. Fig. 1 shows the complete shroud construction and Fig. 2 illustrates the different parts of the constructed wind turbine. The current work has been conducted in the aerodynamics lab using the available wind tunnel which provides air flow at the required speed.

Fig.1 A complete shrouded wind turbine construction

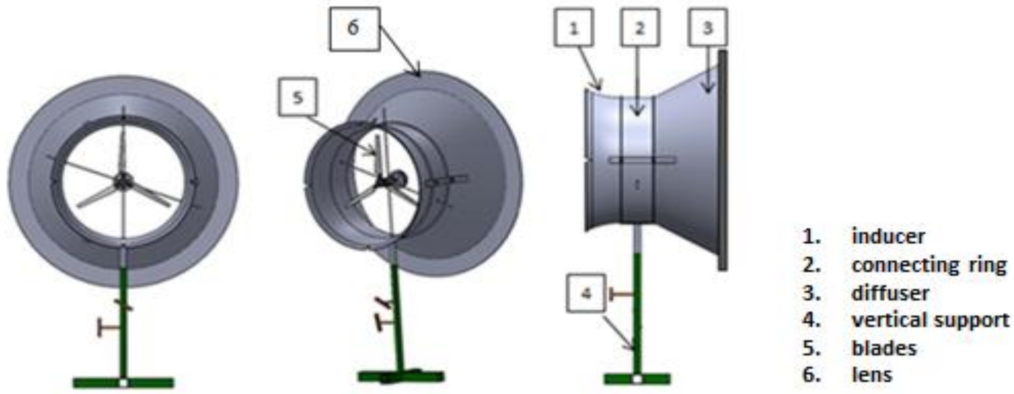
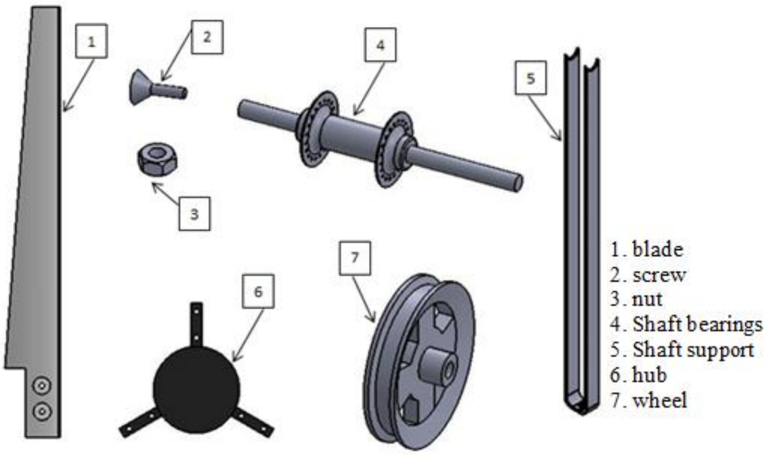


Fig.2 Parts of the constructed wind turbine

The wind tunnel exit is provided with a diffuser to provide a uniform wind speed in the area at which the tested wind turbine is located. The three main factors that influence power output from a wind turbine are air density, blade radius, and wind speed. The air density is almost constant and the blade radius used to calculate the swept area is fixed. In the present work, the turbine blades are manufactured from a PVC pipe of 10.16 cm diameter, 5 mm thickness. The length of the blade is 25.5 cm. Three blades were fastened together to a hub, and then the assembly of three blades was installed on a shaft. On the flow downstream side of the shaft, a wheel of 10 cm diameter (D) is installed for the requirement of brake power calculations. A vertical stand is used to fix the turbine at a certain height. During the current work, the wind speed is measured by a digital anemometer shown in Fig. 3 (a) and the calculations are based on the average wind speed of 11m/s.



The following steps have been followed during the experimental work; the wind tunnel is turned on and a non-contact tachometer (laser type) shown in Fig. 3 (b) is used to measure the turbine rotation speed (RPM) while it is not loaded with weights. The prony brake method is used to measure the torque. The weights are added gradually starting with 200 grams and then increasing by a weight of 50 grams until the turbine brakes. The turbine blade speed (RPM) is measured at each weight. Power coefficient (C_p) and the tip speed ratio (λ) are calculated by applying Eqs. (1) and (5) respectively by using this measured data. The previous procedures are repeated for the different cases in this study. The essential parameters used in the current work calculations are listed in Table 1.

Table 1 parameters used in the current calculations

Parameter	value
$\bar{u}$ *(m/s)*	11
ρ *(kg/m³)*	1.2
l *(m)*	0.255
r *(m)*	0.025
A *(m²)*	0.244
D *(m)*	0.1
Number of blades	3

(a) (b)

Fig.3 Devices used in experimental measurements: (a) Digital anemometer.

(b) Non-contact tachometer (laser type)

3. RESULTS AND DISCUSSION

The case of a bare wind turbine was considered the reference case; in this case, the swept area was not confined so only a fraction of the flow energy is converted into mechanical energy. The highest power coefficient for the bare wind turbine was 0.1969. The illustration of (C_p) against (λ) is shown in Fig. 4 (a).

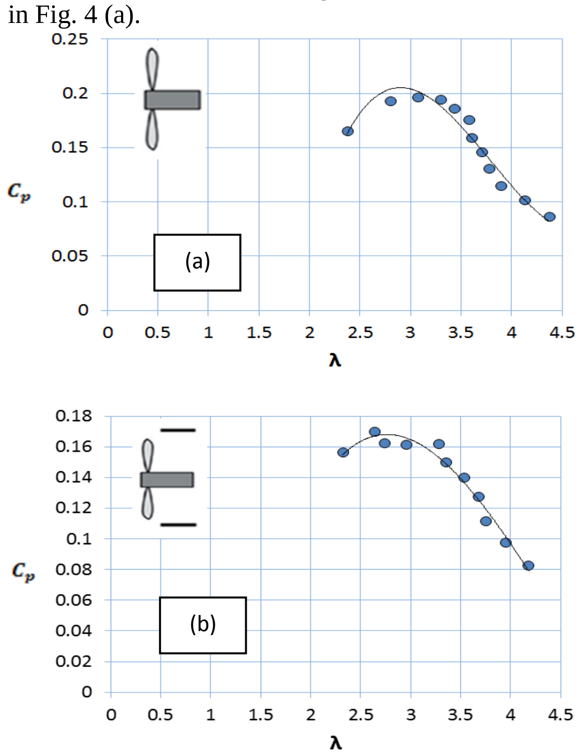


Fig.4 C_p - λ (a) Free wind turbine. (b) Wind turbine with a connecting ring

The second test, to check the effect of installing a connecting ring behind the bare wind turbine on the performance, showed that the maximum C_p in this case as shown in Fig. 4 (b) was 0.1695. Since the presence of a connecting ring could increase the friction losses without a sensible effect on inducing more wind inside the rotor plane. In the third arrangement, the inlet nozzle 'inducer' was attached to the connecting ring around the blades. It has been noticed that the power coefficient C_p increased to 0.2213 that is about (11 %) greater than the C_p of free wind turbine assembly. Adding an inlet nozzle guides and accelerates the air flow inside that leading to an increase in the mass flow rate for a certain free stream wind speed. As a result, the velocity is increased at the rotor plane which increases C_p of the HAWT see Fig. 5 (a).

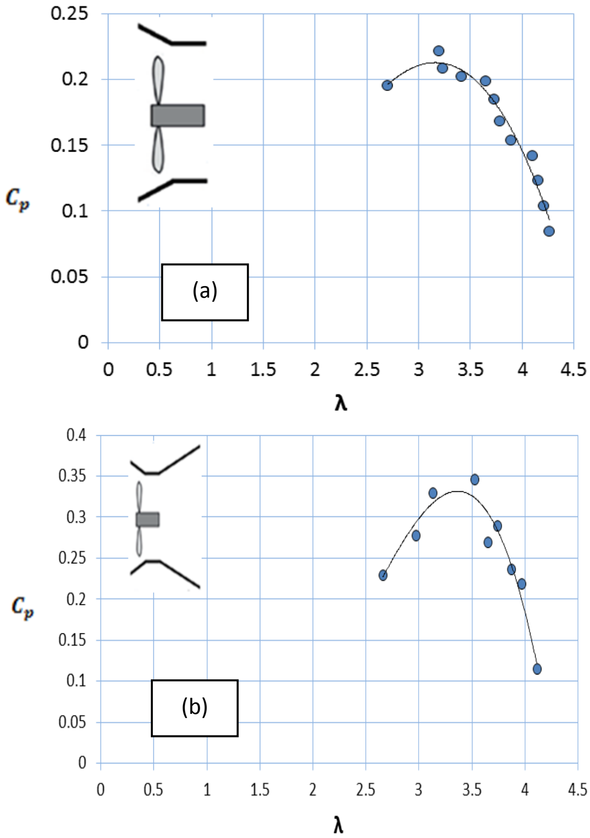


Fig. 5 $C_p - \lambda$ (a) Inducer and connecting ring. (b) Inducer, connecting ring, and diffuser

In the fourth case, a diffuser part was attached to the inducer and the connecting ring in the downstream direction. The results of this case show an enhancement in the maximum power coefficient to be 0.347, which is improved by 36.2 % compared to the third case 'inducer and connecting ring', and 43.26 % to the bare turbine. The diffuser could increase the turbine output by reducing the pressure at the wind turbine exit then the mass flow and the produced power efficiency of the wind turbine increased [4], [9].

The fifth case was carried out by adding a lens (flange) to the diffuser outlet to construct a full shroud. For this construction, the best performance obtained at the power coefficient equals 0.35 as shown in Fig. 6 (a). This case resulted in an improvement of the maximum power coefficient by 43.74% greater than the bare turbine. The flanged diffuser could reduce and destroy outer kinetic energy at the diffuser exit and permit the inner flow with lower energy to pass through to the atmosphere. The function of the lens is to generate a low-pressure region adjacent to the diffuser exit by vortex formation which results in more flow rates through the diffuser shroud.

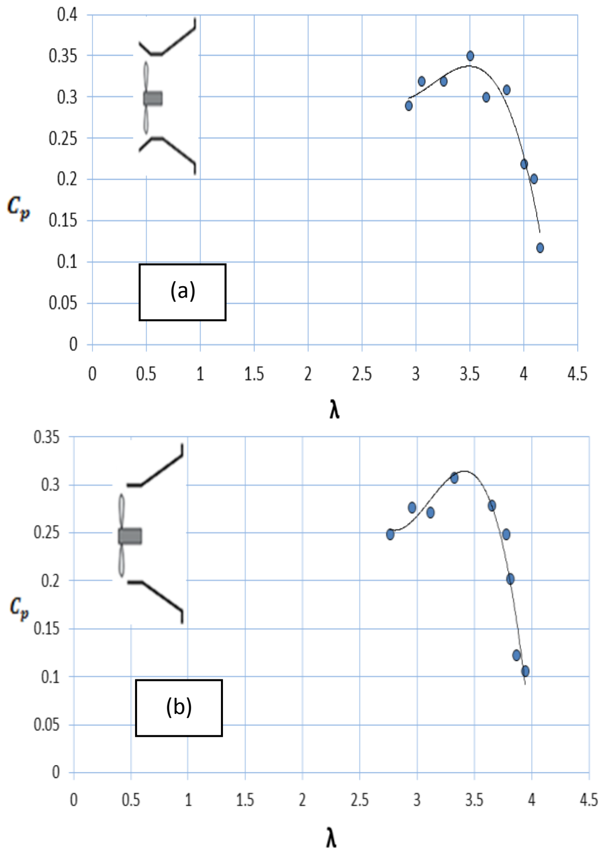


Fig. 6 C_p - λ (a) Inducer, connecting ring, diffuser, and lens. (b) Connecting ring, diffuser, and lens

To reduce the construction cost some parts of the shroud should be removed from the assembly. For this purpose, in the 6th case, the inlet inducer is removed and the connecting ring attached to the flanged diffuser is examined, under the same working conditions, the highest power coefficient is reduced from 0.35 in the full shroud case to 0.308. Although the performance, in this case, was lower than the case of the full shroud as shown in Fig. 6, it improved the performance over the bare turbine by 36.07 % and the case of inducer-connecting ring assembly by 28.15 % as shown in Fig. 7.

For performance comparison, the 2nd case which has a connecting ring behind the blades gives the lowest (C_p) even less than the bare HAWT. In the 3rd case, the inducer led to a slight improvement in the performance. Adding a diffuser to the combination of inducer and connecting ring as shown in the 4th case enhanced the performance considerably. For a full shrouded wind turbine the performance has increased significantly to 0.35 at a tip speed ratio of 3.5 see Fig. 7.

Fig.8 Effect of shroud components attached to a small HAWT

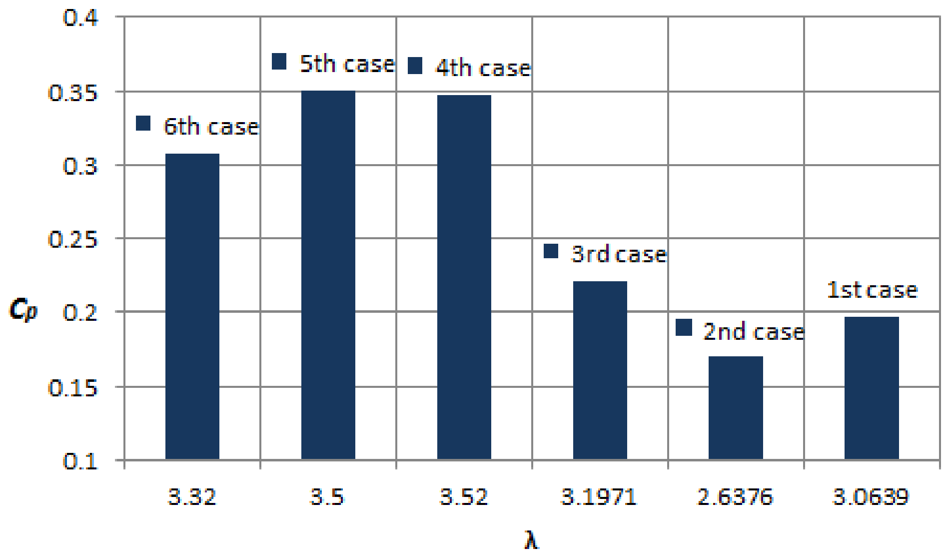
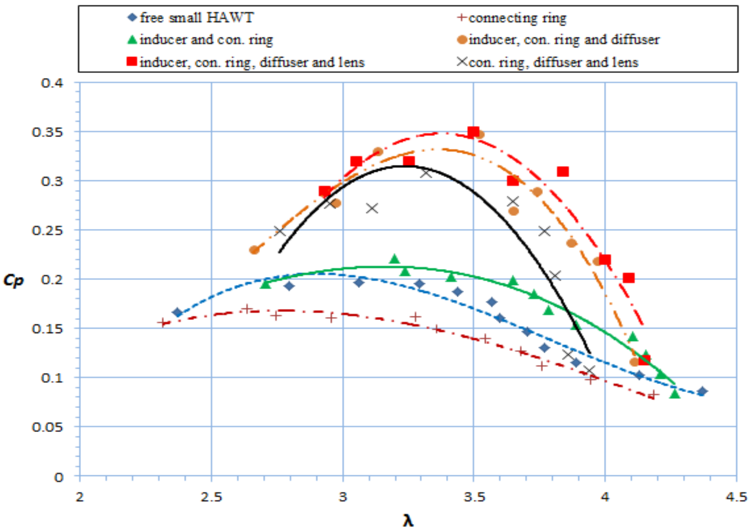


Fig.7 Power coefficient (C_p) against tip speed ratio (λ) for different cases

Attaching a diffuser to the assembly enhances the wind turbine performance but moves the performance curve and the maximum C_p to a higher tip-speed ratio 'λ' as shown in Fig. 5 (b). Every component of the shroud in the HAWT plays a certain role in its performance; Fig. 8 illustrates the effect of these different components. Adding an inducer enhances the performance and provides stable running conditions over a wide range of tip speed ratios. The turbine augmented with a full shroud has the highest performance under the specific conditions of operation mentioned in this work.

For the best performance, the wind turbine has to work under stable conditions for a wide range of tip speed ratios. Referring to the mentioned Figure, the first 3 cases can provide stable running conditions for the HAWT, despite the lower C_p if compared to the cases of having a diffuser in the assembly.



4. CONCLUSIONS

A small horizontal-axis wind turbine was erected to carry out an experimental investigation on the effect of different shroud components attached to the bare HAWT such as connecting ring, inducer, non-flanged diffuser, and flanged diffuser. The tip-speed ratio 'λ' and the power coefficient (C_p) have been calculated at an average wind speed of 11 m/s. It is concluded that:

1. The shrouded small HAWT has achieved the highest power coefficient (The best efficiency). Since the shroud increases the amount of air flow rate passing through the rotor.
2. The small horizontal axis wind turbine with connecting ring reduces the power coefficient because the main function of the shroud
3. (increase the amount of air flow rate passing through the rotor) could not be accomplished since the ring is placed behind the blades.
4. Adding an inducer enhances the performance and provides stable running conditions over a wide range of tip speed ratios which means a high operating range.
5. Attaching a diffuser to the assembly of a small horizontal-axis wind turbine increases the power coefficient. However, it moves the performance curve and the maximum power coefficient (C_p) to a higher tip-speed ratio 'λ'. The diffuser effect reduces the operating range if compared to the case of adding an inducer.
6. If the inlet inducer is removed from the shroud both the construction cost and the maximum power coefficient are reduced. Although the performance, in this case, was lower than the case of the full shroud it improved the performance over the bare wind turbine and the case of the inducer-connecting ring.

The current study investigates shroud components that affect a small horizontal axis wind turbine performance. It was found that the shrouded small HAWT can achieve the best power coefficient in comparison with bare HAWT.

NOMENCLATURE

CFD	: Computational fluid dynamics
C_P	: Power coefficient
HAWT	: Horizontal axis wind turbine
L	: Length of the blade
R	: Radius of the hub
R_b	: Total blade length
$P_{m.out}$	: Mechanical power produced
$P_{w.in}$	: Wind power
T	: Torque
ω	: Angular velocity of blades
ū	: Average wind speed.
λ	: Tip speed ratio
γ	: Speed-up ratio
η	: Efficiency
ρ	: Air density

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تأثير مكونات الغطاء على أداء توربينة رياح صغيرة ذات محور أفقي

الملخص

تم اختبار نموذج لتوربين رياح صغير ذات محور أفقي بشكل تجريبي لإظهار تأثير مكونات الغطاء على الأداء العام للتوربين. كانت الحالة المرجعية هي توربينة رياح مكشوفة. أجزاء الغطاء المختلفة هي حلقة ربط ، ومحفز ، وناشر ، ومجمع نهائى. معامل القدرة الأقصى (C_p) لـ HAWT المكشوف المستخدم هو 0.1969 (الحالة الأولى). عندما تم توصيل حلقة الربط بالحالة المرجعية (الحالة الثانية) ، انخفض الحد الأقصى لـ C_p إلى 0.1695. أما في (الحالة الثالثة) تم توصيل محفز بحلقة الربط وزاد الحد الأقصى لـ C_p إلى 0.2213 أي حوالي 11 ٪ أعلى من توربينة الرياح المكشوفة. عند إضافة جزء ناشر إلى المحفز وحلقة الربط فى (الحالة الرابعة) زاد معامل الأداء إلى 0.347 والذي تم تحسينه بنسبة 36.2 ٪ مقارنة بالحالة الثالثة و 43.26 ٪ لتوربينة الرياح المكشوفة. في الحالة الخامسة تمت إضافة مجمع نهائى إلى مخرج الناشر لبناء غطاء كامل. بالنسبة لهذا البناء تم الحصول على أفضل معامل أداء عند $C_p = 0.35$ أدى هذا التركيب إلى تحسين الأداء بنسبة 43.74 ٪ ، أكثر من التوربين المكشوف. ولتقليل تكلفة الأنشاء في (الحالة السادسة) تم إزالة محفز المدخل واختبار الاداء فى حالة وجود حلقة التوصيل مع مجموعة الناشر ذات الحواف في ظل نفس ظروف العمل فتم تقليل الأداء إلى 0.308 على الرغم من أن الأداء في هذه الحالة كان أقل من حالة الغطاء الكامل إلا أنه أدى إلى تحسين الأداء مقارنة بالتوربين المكشوف وحالة التوربين المحتوى على مجموعة حلقة الربط بنسبة 36.07 ٪ و 44.97 ٪ على التوالي.