https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: ---------

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

Experimental Study on the Performance of Spiral Wind Turbine

Tarek A. Ghonim[1], Ahmed S. Hegazy[1], Alaa Maher[2], and Mohammed S. Farag[1]

[1]Department of Mechanical Power Eng., Faculty of Eng., Menoufia University, Egypt.
[2]M.Sc. Candidate,
(Corresponding author: tarek_ghonim@sh-eng.menofia.edu.eg)

ABSTRACT

For urban commercial use of Archimedes spiral horizontal axis wind turbine, its performance involving power output, power coefficient, and effect of aspect ratio or rotor dimensions needs to be enhanced. In order to assess the performance of the turbine, an experimental set-up was fabricated with all necessary measurements. Additionally, the experimental work was conducted on four different Archimedes spiral rotor experimental models having different dimensions and consequently different aspect ratios. The measurements were carried out at various wind velocities. Comparisons among all experimental rotor models were conducted aiming to discover the effect of the rotor dimensional parameters on the performance of Archimedes spiral wind turbine. The results confirmed that increasing both Archimedes spiral rotor diameter and length and consequently the rotor aspect ratio enhanced greatly the power coefficient within the experimental investigation range. The minimum cut-off speed for model (1) was observed to be about 4 m/s. Lastly, model (1) showed a maximum power coefficient of 0.17 while model (4) had the worst performance.

Keywords: *Archimedes spiral wind turbine; coefficient of power; tip speed ratio; rotor aspect ratio.*

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1. Introduction

Wind turbine is used to convert wind energy into mechanical and electrical energies. The principle behind this energy conversion is that wind moving with certain velocity produces rotary motion of the blade rotor. The rotor movement depends mainly on the shape of the blade. The more efficient the blade is, the more becomes the rotary motion and consequently, the more is the output of the turbine [1].

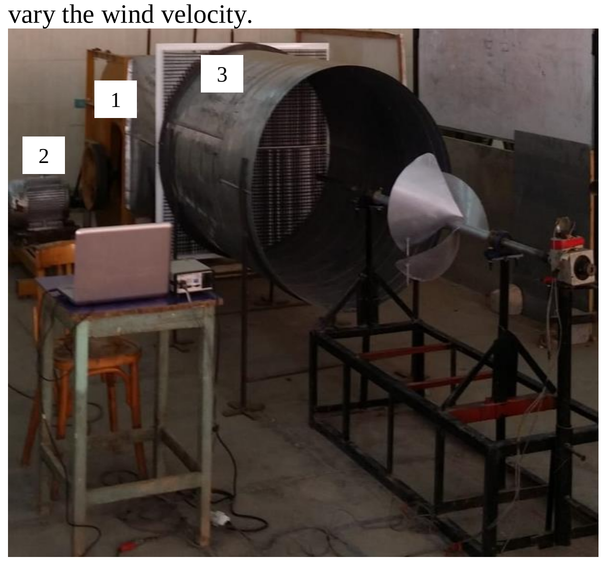
There are two general types of wind turbines: horizontal and vertical axes. The axis of the vertical rotor turbine is perpendicular to the ground. While that of the horizontal rotor turbine is parallel to the ground. Many designs are available for both types having certain drawbacks and advantages. However commercially, the horizontal axis turbines are more available than vertical axis turbines [2].

For many years, the experimental and computational fluid dynamics (CFD) technique have proved to be an efficient tool for assessment of wind turbines performance through measurement and numerical prediction of the generated torque and power coefficient [3]. Most experimental and CFD investigations have been carried out to study the effect of tip speed ratio, diameter and length/height of the turbine rotor on the turbine performance [4-6]. Arman and Kyung [7] evaluated aerodynamically and structurally a horizontal Archimedes spiral wind turbine. The CFD simulation of the aerodynamic performance of the blades was done for different values of inlet velocity. It is found out that, the spiral turbine maximum efficiency takes place when the Cp is at its peak value. Kyung et al. [8] studied the aerodynamic characteristics of an Archimedes spiral wind turbine blade both experimentally and numerically. At the blade tip, a maximum pressure differences were seen, indicating that the most wind energy can be harnessed at outer part of the blade. The numerical and experimental results showed a spiral shaped tip vortices. Seong et al. [9] studied experimentally the aerodynamic performance of small wind turbine with 500 W Class through a wind tunnel. The characteristics of performance of an Archimedes spiral wind turbine illustrated a similarity with modern multi-blade turbine and the maximum power coefficient as a function of the tip speed ratio. Kyung et al. [10] investigated experimentally and numerically the aerodynamic characteristics of an Archimedes spiral wind turbine for urban-usage. The simulated coefficient of power (Cp) showed that this type of wind turbine produced about 0.25, which is relatively higher compared to other types of urban-usage wind turbine. The aerodynamic characteristics showed that an Archimedes spiral blade wind turbine is suitable for small scale urban usage. Shashank et al. [11] investigated designing and fabricating a horizontal axis small scale Archimedes spiral wind turbine. For commercial purposes, an approximately 2.5 m/s minimum cut-off speed is used making Archimedes wind turbine perfectly suitable for areas with low wind speed. Also, the proposed turbine design was capable for generating high torque at this low wind speed making it preferred for power generation at small scales. Patil [12] Designed, fabricated and analyzed a Fibonacci spiral horizontal axis wind turbine. The spiral blade wind turbine is used for electricity generation in both urban areas and industrial purposes. Additionally, it is reported that the blade speed increases when the wind velocity is increased, and thus the efficiency of the turbine is increased as well. The wind speed should be from 18 to 25 m/s for optimum performance of the industrial wind turbines. Kanakaraddi et al. [13] investigated the design and analysis of Archimedes wind turbine. They found that when the inflow wind velocity increased, the pressure differences became larger. The pressure differences at the blade root region were smaller, while larger at the blade tip. Which means that most of energy can be extracted near the blade tip like a three blade horizontal axis wind turbine. Jang et al. [14] analysised the performance of an Archimedes spiral wind turbine by simulation and field test. A maximum power coefficient of 0.293 was found to be at a corresponding tip speed ratio of 2.19. Labib et al. [15] studied numerically the effect of aspect ratio on aerodynamic performance of Archimedes spiral wind turbine. The results highlighted that the less aspect ratio with forward elongation, the more resulting power coefficient. Nawar et al. [16] investigated experimentally and numerically the blade design effect on Archimedes spiral wind turbine performance. The variable-angle design produced a power increase of 14.7% over the fixed-angle design.

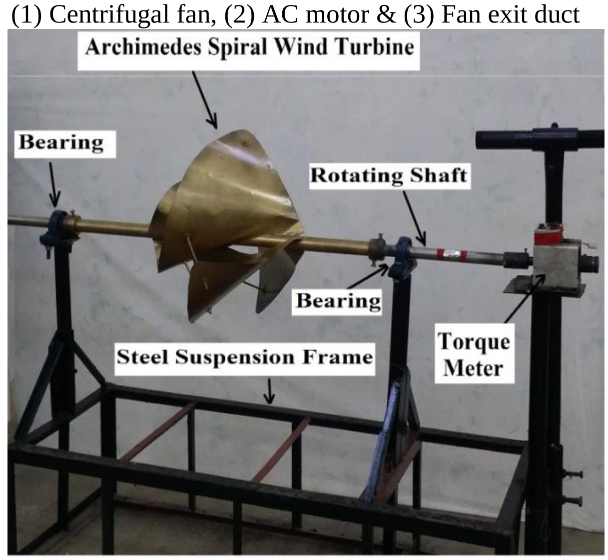
Because Archimedes spiral wind turbine is considered as one of the most promising commercial horizontal axis wind turbine and that little research work was found in the literature concerning its optimum design, the present experimental work is dedicated to performance analysis and enhancement of Archimedes spiral wind turbine. The analysis and enhancement of this turbine included the effect of different geometrical designs where two main parameters were changed at variable wind velocity. These parameters are the diameter and length of the spiral rotor.

2. Experimental Set-up

The testing apparatus shown photographically in Fig. (1) is used to conduct the experimental work. As clearly shown in the figure that it contains two main portions. The first portion is the artificial wind source belonging to the advanced fluid mechanics laboratory which is consisted of a centrifugal fan (blower), an AC motor and an exit duct of a centrifugal fan. The second one is a constructed Archimedes spiral wind turbine which consists of a spiral three-bladed rotor, two bearings, rotor shaft, steel suspension frame, and torque meter. The artificial wind source attained a maximum velocity of 15 m/s at the exit section of its circular duct. A motor Speed Controller is used to vary the wind velocity.



(a) Artificial wind source
(1) Centrifugal fan, (2) AC motor & (3) Fan exit duct



(b) Archimedes Spiral Wind Turbine
(Spiral three-bladed rotor, bearings, rotor shaft, steel suspension frame, and torque meter)

Fig. (1) A photograph of the Experimental Set-up

Archimedes three-bladed spiral rotors with four different geometrical dimensions (experimental models) were investigated experimentally in the current study. The spiral rotor blades are fabricated from galvanized iron sheets. The specifications of these four experimental models are listed in Table (1). Moreover, these four experimental rotor models are depicted photographically in Fig. (2) at two different views.

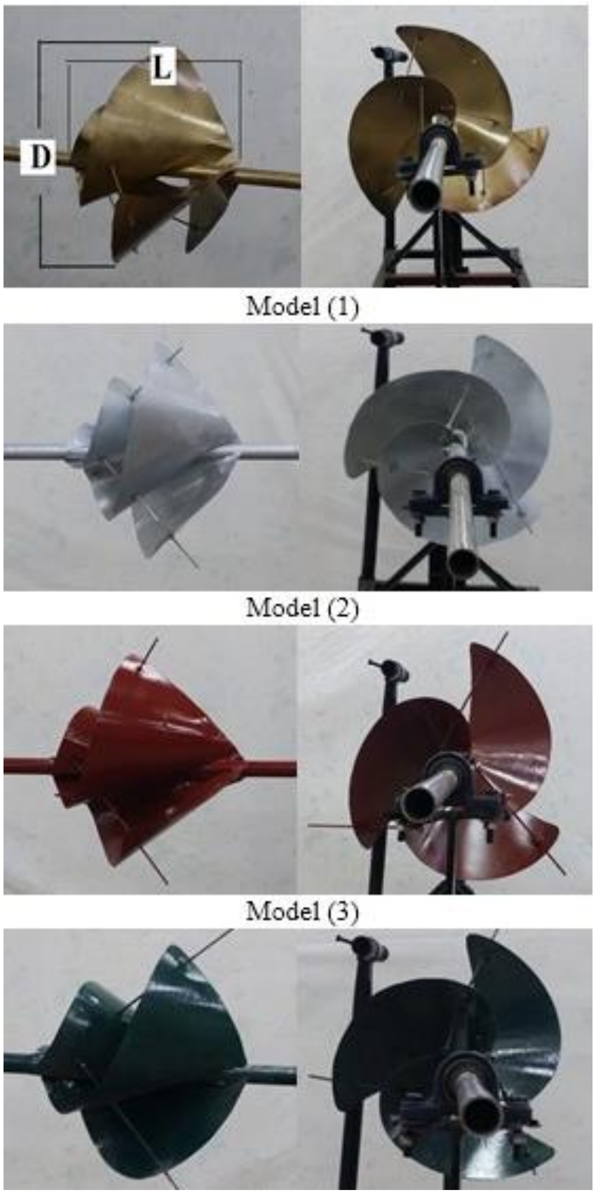


Fig. (2) Photographs of the four experimental rotor models at two different views.

3. Experimental Procedures

Archimedes three-bladed spiral rotor is placed in front of the fan exit circular duct mounted on the steel suspension frame at a distance of about 1 meter. A rope break is used to vary the mechanical load on the torque meter which is coupled to the rotating shaft by nylon-string connected to a weighing pan.

For measurement of wind velocity, an air anemometer is used as shown in Fig. (3). A digital laser tachometer illustrated in Fig. (4) is used to measure the speed of rotation of the spiral rotor shaft of the turbine. Additionally, Fig. (5) illustrates the digital torque meter used for measurement of the power generated by the turbine rotor. The operation ranges, model and accuracies of the measurement devices are stated in the captures beneath the photographs of the devices shown in Figs. (3, 4 and 5).

In reality, wind turbines can never harness all the wind power when wind passes through the blades of the turbine rotor, which means that some part of the kinetic energy of the wind is transferred to the rotor and the remaining of the energy leaves the rotor. Consequently, the wind power portion that is transformed to mechanical power by the rotor is termed as the efficiency that is usually defined as the coefficient of power, Cp which is frequently used to assess the performance of the turbine. Another important parameter is the tip speed ratio, λ which connects both blade tip peripheral velocity with the wind velocity. These two previously mentioned parameters can be calculated from Eqns. (1) and (2) respectively.

$$\mathrm{Cp} = \frac{\mathrm{T}\,\omega}{0.5\,\rho\,\mathrm{A}\,\mathrm{V}^3} \tag{1}$$

$$\lambda = \frac{\omega\,\mathrm{R}}{\mathrm{V}} \tag{2}$$

All experiments were conducted for several times to confirm the repetition of the experimental results. The uncertainties of the power coefficient, and tip speed ratio were about 1.92% and 0.83% respectively using Kline-McClintock formula [17].

Fig. (3) A photograph of air anemometer. Operating range of (0.4 – 25.0) m/s, and an accuracy of $\pm$0.2 m/s (Model: AM-4206 Anemometer)

Fig. (4) A photograph of digital laser tachometer. Operating range of (1-10000) rpm, and an accuracy of $\pm$ 0.5 rpm (Model: GTC-TA110 laser tachometer)

Fig. (5) A photograph of the torque meter. Operating range of (-5 to + 5) N.m, (Model: MCRT-48200v Compact digital torque meter and an accuracy of $\pm$ 0.15 Nm)

4. Experimental Results and Discussion

The experimental results concern with analyzing the performance of spiral wind turbines in an attempt to enhance its efficiency. Hence, the effects of some crucial parameters are presented and discussed such as wind velocity, V and rotor aspect ratio, AR= (L/D). Where, L is the blade length and D is the rotor outer diameter.

4.1 Effect of Wind Velocity

The wind velocity, V effect on Archimedes spiral rotor performance for four different experimental models is illustrated in Figs. (6 to 9). The figures show the power coefficient, Cp variation with the tip speed ratio, λ at three various wind velocities for Models (1 to 4). At all tip speed ratios and for all the studied experimental models it is observed that, increasing the wind velocity enhanced the power coefficient of the turbine which means that the power extracted from the wind by the blade increased as well. Additionally, increasing the wind velocity will consequently increase wind energy harnessed. Hence, the rotor angular velocity increases which manifests itself as a rise in the tip speed ratio, λ which shifts the maximum power coefficient to the right at larger tip speed ratio.

According to Kanakaraddi et al. [13], both drag and lift forces are used in Archimedes spiral wind turbines to harness wind energy on its rotor blades giving it the advantage of being installed with less height from ground and being more efficient that other types of small wind turbines. Another important advantage which was distinctively noticed during the measurements is that the turbine performance represented in its maximum power coefficient rotor was less sensitive to wind direction, (yaw angle). This means that this type of turbines is more suitable for areas with variable wind direction as a yawing mechanism will have a response time which will rarely affect the power extracted. Furthermore, the cut-off speed of the Archimedes spiral turbine was registered to be generally less than 5 m/s which is consistent with previous finding of Patil, [12]. The cut-off speed is the minimum speed of wind required to rotate the blade. However for model (1), the cut-off speed was found to be about 4 m/s which indicates that the dimensions of the spiral rotor play a crucial role in performance enhancement of this particular type of wind turbines.

Table (1) Specifications of Archimedes spiral rotor dimensions

Models	D, [cm]	L, [cm]	L/D
Model (1)	55	60	1.1
Model (2)	55	50	1.1
Model (3)	50	50	1
Model (4)	45	50	0.9

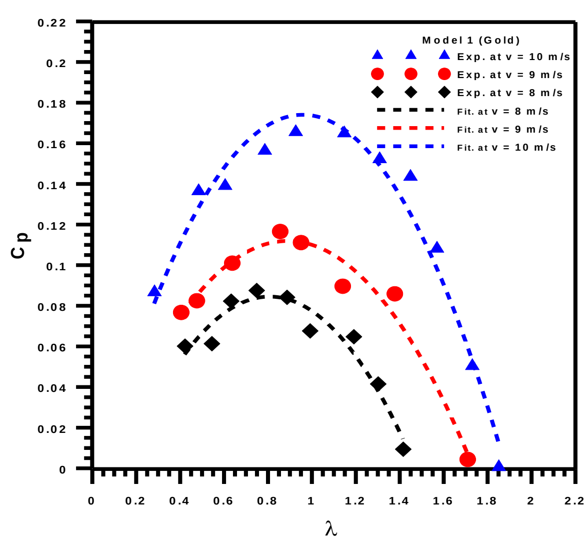


Fig. (6) Power coefficient variation with tip speed ratio at various wind speeds values for Model (1)

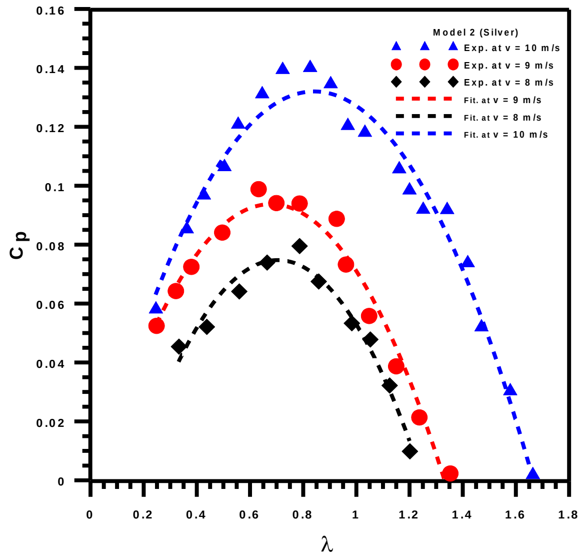


Fig. (7) Power coefficient variation with tip speed ratio at various wind speeds values for Model (2)

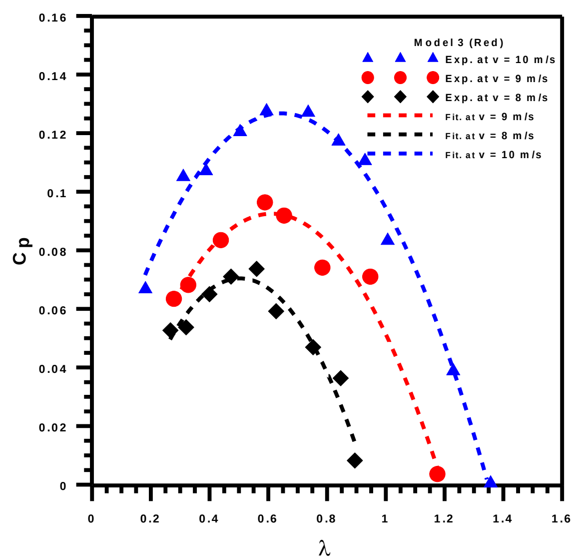


Fig. (8) Power coefficient variation with tip speed ratio at various wind speeds values for Model (3)

4.2 Effect of Rotor Dimensions

A comparison between four experimental rotor models is presented in Figs. (10,11 and 12) at three different wind velocities, namely 8, 9, and 10 m/s. Model (1) showed the highest power coefficient while Model (4) had the worst power coefficient. This is apparently due to that model (1) has both the largest diameter and length. Contrarily, model (4) has both the smallest ones. Also for different diameters at constant length of 50 cm, as listed in Table (1) increasing the spiral rotor diameter enhanced the power coefficient of the turbine which is depicted in models (2, 3 and 4). When the spiral rotor diameter increases, the power production increases because the swept area of the rotor blade increases. As the swept area of the blade increase it extracts more kinetic energy from the wind.

Hence the speed of rotor increases and then the power production increases as well. On the other hand, if models (1 and 2) are compared where both have the same diameter it can be seen that increasing the rotor length enhanced the power coefficient as well. Increasing the rotor length may consequently increase the residence time of the air inside the rotor which promotes the momentum transfer from the wind to the blades of the rotor.

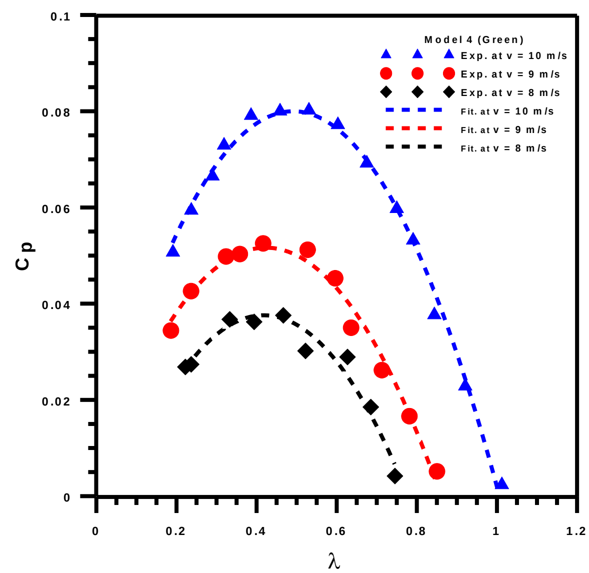


Fig. (9) Power coefficient variation with tip speed ratio at various wind speed values for Model (4)

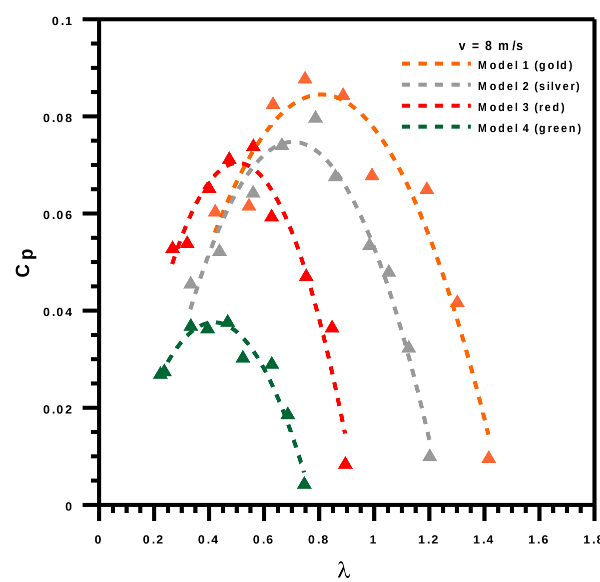


Fig. (10) Power coefficient variation with tip speed ratio for difference Models at constant wind speed value (V = 8 m/s)

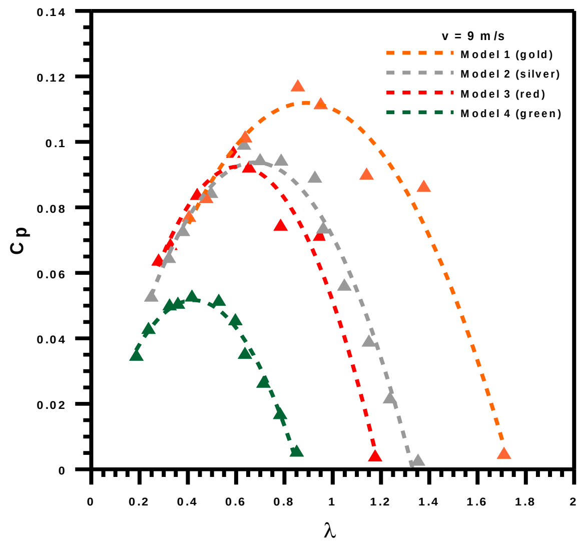


Fig. (11) Power coefficient variation with tip speed ratio for difference Models at constant wind speed value (V = 9 m/s)

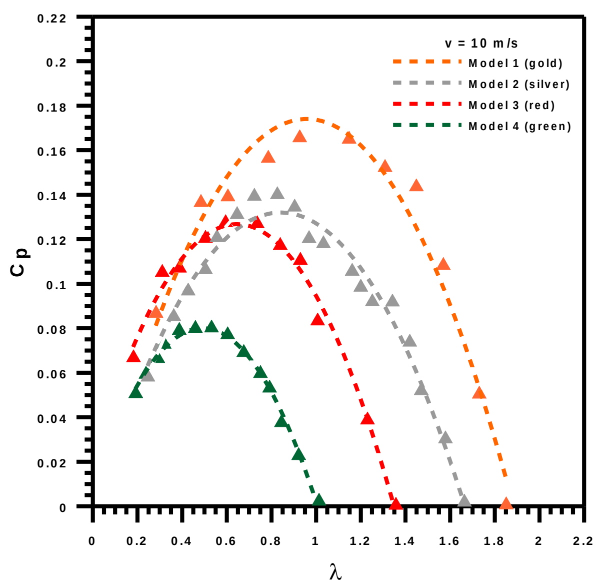


Fig. (12) Power coefficient variation with tip speed ratio for difference Models at constant wind speed value (V = 10 m/s)

To conclude, increasing the aspect ratio generally enhanced the power coefficient within the investigation range and consequently the power extracted from the wind.

However, the investigated experimental models can only confirm the obtained results within a limited aspect ratio range (0.9-1.1). Hence, an extension of the present work will consider wider aspect ratio ranges of experimental models. Furthermore, CFD will be used to explain the flow behavior inside the rotor blades to gain the best insight on this wind turbine in a future continuation.

5. Conclusions

Present experimental work concerned with performance analysis and enhancement of Archimedes spiral wind turbine using four different experimental rotor models. The analyzed and compared results can be summarized as:

1. The results confirmed that increasing both Archimedes spiral rotor diameter and length and consequently the rotor aspect ratio enhanced greatly the power coefficient within the experimental investigation range.
2. Model (1) showed the highest power coefficient of about 0.17 while model (4) had the worst performance compared to other models.
3. The minimum cut-off speed required to operate the rotor experimental model (1) was about 4 m/s while other models were about 5 m/s meaning that the turbine rotor aspect ratio is a crucial factor in determining minimum starting wind velocity.
4. The turbine performance represented in its maximum power coefficient rotor was less sensitive to wind direction, (yaw angle) making it suitable for urban areas with variable wind direction and large scale industrial purposes where it is economically sustainable.

6. Nomenclature

Cp	Power coefficient, [-]
λ	Tip speed ratio, [-]
V	Velocity of wind, m/s
D	Outer diameter of rotor, [m]
L	Length of rotor, [m]
R	Rotor outer radius, (D/2), [m]
AR	Rotor aspect ratio, [-]
A	Rotor swept or projected area, [-]
T	Mean torque of the
ρ	Air density, [kg/m3]
ω	Rotor angular velocity, [S-1]

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