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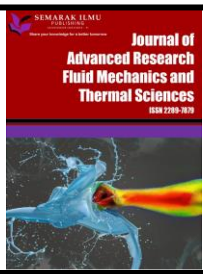


# Aerodynamic Performance Investigation of a Small Horizontal Axis Wind Turbine with Multi-Airfoil Blade Profiles of SD2030 and E231 Using Wind Tunnel Experiments and BEM Theory Method

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**ABSTRACT**

The goal of this study is to investigate the performance of a small horizontal axis wind turbine blade at wind speeds of lower than 5 m/sec numerically and experimentally. The rotor blade has a diameter of 0.7m and consists of two airfoils profile: the thin airfoil SD2030 selected at the outboard region, and the thick airfoil E231 at the inboard region. The former airfoil, SD2030, is highly recognized for aerodynamic performance as it is suitable for low Reynolds number (Re), while the latter airfoil E231 is likewise appropriate for low Re flow but has a higher thickness-to-chord ratio which acts as structural support and good strength at the hub. The selected airfoils were analyzed using QBlade software based on XFOIL and Blade Element Theory (BEM) for different Reynolds number. Using a low-speed wind tunnel and Reynolds number ranging from $1x10^5$ to $5x10^5$, experiments at pitch angles of 5° were conducted to determine the variation in torque and predict blade performance. The results reveal that the turbine with two hybrid different airfoil profiles have achieved a better start-up response at low wind speed of 1.5 m/s and a high-power coefficient of 0.34 with 3.7 tip speed ratio. The turbine can be used to generate a power of 0.5W at 1.5 m/s and a maximum power harvest of up to 20W at a wind speed of 7m/sec. The turbine's performance compared to other small wind turbines from the literatures demonstrate good performance and the results obtained from wind tunnel data were found in satisfactory agreement with the results provided by the BEM code.

## 1. Introduction

Energy has now become the most crucial entity for economic and social growth in the ever-expanding agricultural, industrial, and residential activities of this global village. However, the continuously uprising cost of fossil fuel and its ever-swollen greenhouse gas emissions to the atmosphere which contributes to global warming have made it futile to use. Utilizing renewable

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energy sources more efficiently, which come from naturally occurring processes, is now one of the primary motivations. Among the sources of renewable energy, nowadays, wind energy has become more popular and profitable for sustainable development due to its low cost, reliability, and steady and wider availability [1]. Over the last 10 years, the production of wind energy has increased by 30% [2]. Despite its many advantages, however, it reveals some major drawbacks, like, disruption of generation, as it is susceptible to climatic fluctuations. Therefore, more and more sophistication, calibrations, and advancement of design, planning, and control optimization techniques are required for the better use of wind energy production. Utilizing wind energy as a renewable resource irrespective of small or large project, the wind energy systems convert the kinetic energy of wind into mechanical power or electricity using the smart complex system from the areas of aerodynamics and mechanical, electrical, and control engineering. Propeller-type rotors are used to spin the generators to generate electricity. The energy transferred to the rotor by the wind depends on the air density, the swept area of the rotor, and wind speed [3-5]. Therefore, several factors influence the efficiency of a wind turbine, which include its type, blade geometry, and wind velocity available. Of which, the blade is considered one of the key components to capturing wind energy. It plays a vital role in the whole wind turbine system.

Small Wind Turbines (SWTs) reveal increasing to contribute to the energy needs of both isolated and grid-connected consumers. Unlike large or gigantic horizontal axis wind turbines (HAWTs) that are located in areas only available with optimum wind conditions, SWTs are required for producing power without necessarily the best of wind conditions [6-8]. SWTs are mostly situated within 100 m above sea level, which corresponds to the lowest part of the planetary boundary layer (PBL). Within the PBL, turbulence is produced by the laminar airflow, however, different obstacles and topology slow it down. This leads to the flow around the blade which can separate at a low Reynolds number of lower than $5 \times 10^5$. Typically, flow separation happens after the flow transitions to turbulence at low Reynolds numbers. However, the flow separates even while the boundary layer remains laminar. Laminar separation can cause the development of laminar separation bubbles, which increase the drag of the blade. As the separated laminar flow is invigorated it returns to the surface as turbulent flow, forming what is commonly called a separation bubble as Figure 1 [58]. A separation bubble instigates the boundary layer to thicken above it, resulting excessive increase in pressure drag which finally a loss in aerodynamic lift and noise [9-11]. Therefore, a separation bubble reduces a turbine's start-up ability and power coefficient by reducing the overall aerodynamic performance of an airfoil [12-16]. Consequently, designing a small wind turbine, it is necessary to have a good start-up response to low wind speeds in order to generate the maximum possible power. A typical airfoil not designed for a low Reynolds number can degrade the blade's performance. Many thin airfoils have been developed to work at low Re and reduce the influence of the separation bubble, such as the S1223 and SD20301 [17-20], and more examples of low Re airfoils are: S1210, S1221, S1223, SH3055, FX-631 37, E387, SG6040, SG6041, SG6042, SG6043, Aquila, S822, SD2030, S834, NACA 632xx, and NACA 4418 [21-31].

Therefore, the present study discusses the results of the design and aerodynamic performance of a 0.70 m diameter SWT blade that is capable to operate near the ground level where the wind speed is of the order of a few meters per second. Several design parameters of the turbine were optimized using numerical and experimental techniques, including blade geometry, blade number, tip speed ratio, different pitch angles, and different low wind speeds. To evaluate the aerodynamic performance of the final design, wind tunnel experiments were accomplished, and the turbine showed a better start-up response at very low wind speed of 1.5 m/s. The turbine was found very efficient which produce a power coefficient ranging from 32% to 34%. The turbine generates 0.5W electric power at a wind speed of 1.5m/s which increases to 20 Watts at a wind speed of 7m/s. In fact, this turbine is one of the very few wind turbines that have a rated wind speed below 2 m/s. A major advantage of this SWT is that its performance is comparable to other highly efficient SWTs whose rated wind speeds exceed 10m/s. Despite its low power output, the application areas of this SWT are not to be disregarded. As a modular, portable, and light in weight, this turbine could be used to serve as a carry-on modular windmill for powering portable electronic devices like cellular phones, small radios or walky-talky, handheld GPS devices, various electronics home apparel including the home security system. Moreover, health monitoring sensor nodes used on bridges and highways could be easily incorporated with this SWT.

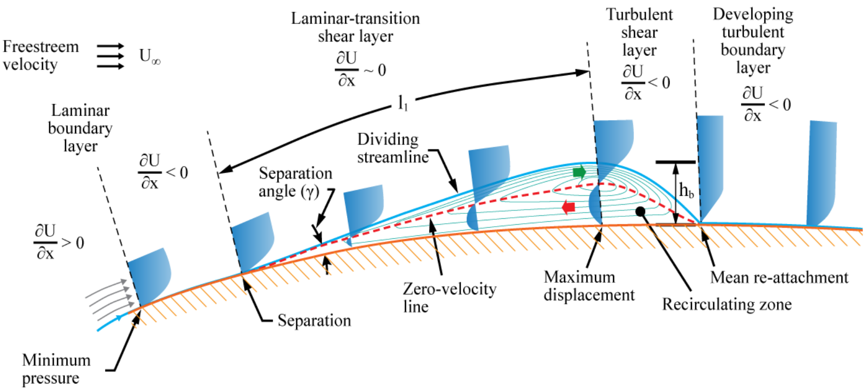


**Fig. 1.** Description of a laminar separation bubble [58]

### *1.1 Low Reynolds Number Airfoils for Wind Turbines*

Modern wind turbine uses airfoils as blade profile, making the airfoil selection critical to wind turbine design [32-35]. many airfoils operating at low Reynolds numbers can reduce the influence of the separation bubble. A common feature of low Reynolds number airfoils is a piecemeal transition ramp on the upper surface. Consequently, the trailing edge must be cusped to enhance the airfoil's camber, therefore, the aerodynamic loads. The cusped trailing edge can make the fabrication of the turbine tricky due to its fragile structure [30]. As a result, airfoils with a high cusped trailing edge are not suitable candidates for blade profiles in this study. Figure 2 demonstrates 12 airfoils suitable for low Reynolds number flow regime applications.

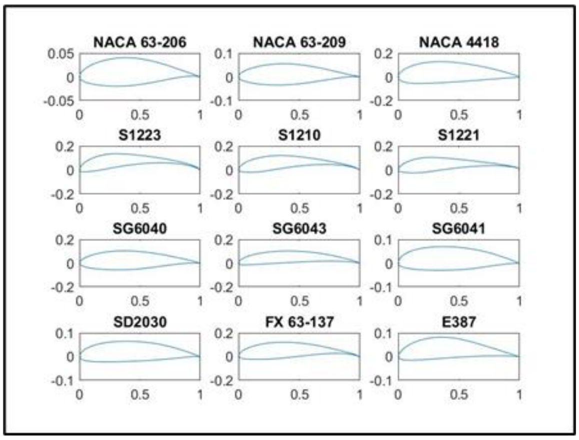


**Fig. 2.** Low Reynolds number airfoils

Among those airfoils, the SD2030 airfoil profile has a slight cusped trailing edge, as shown in Figure 2. It was proven successful for wind turbines with low wind speeds [21,30,36]. It has good criteria, such as having a high L/D occurring at a wide variety of attack angles and having a low drag knee [22-23]. The SD2030 airfoil has an 8.56% thickness ratio, as stated in Table 1, which may weaken the blade construction at the inboard part. The E231 airfoil profile was originally designed for sailplanes; it has a thickness ratio of 12% and a camber ratio similar to the SD2030 airfoil. The two airfoils configuration is shown in Figure 3. The maximum camber occurs at positions 39.4% and 45%, respectively which means both airfoils can be connected smoothly without a sharp twist.

**Table 1**
Thickness and camber ratio of the airfoils SD2030 and E231

| Airfoil | Thickness | Camber | Max Camber Location |
|---|---|---|---|
| SD2030 | 8.56% | 2.23% | 45.3% |
| E231 | 12.34% | 2.46% | 39.4% |

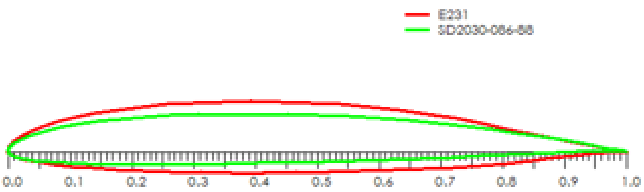


**Fig. 3.** SD2030 airfoil shape vs. E231 airfoil shape [22-23]

## 2. Wind Turbine Description

This section describes the configuration of the two-airfoil wind turbine blade and how it differs from the single-airfoil turbine. Table 2 shows the taper ratio and the Twist distribution of the two-airfoil turbine. The aerodynamic part of the blade is 0.24 m. The airfoil SD2030 is used on half of the blade at the outboard region toward the blade tip, while the airfoil E231 is used on the other half at the inboard region toward the blade root. A circular cylinder is attached to the blade to link it to the hub and provide structural support. Figure 4 depicts the isometric view of the two-profiles blade.

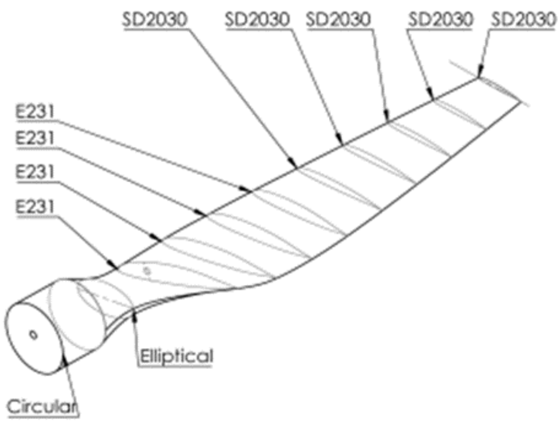


**Fig. 4.** Isometric view of the two-profile blade

**Table 2**
The two-airfoil turbine's geometry and design parameters

| R (m) | Airfoil | Chord length (m) | Twist angle |
|---|---|---|---|
| 0.24 | SD2030 | 0.03 | $0^0$ |
| 0.21 | SD2030 | 0.0375 | $0.6^0$ |
| 0.18 | SD2030 | 0.045 | $1.3^0$ |
| 0.15 | SD2030 | 0.05248 | $2.3^0$ |
| 0.12 | SD2030 | 0.06 | $3.6^0$ |
| 0.09 | E231 | 0.0675 | $5.3^0$ |
| 0.06 | E231 | 0.075 | $8^0$ |
| 0.03 | E231 | 0.0825 | $12.2^0$ |
| 0 | E231 | 0.09 | $20^0$ |
| -0.08 | Elliptic | 0.04 x 0.02 | $0^0$ |
| -0.06 | Circular | D = 0.04 | $0^0$ |
| -0.05 | Circular | D = 0.04 | $0^0$ |
| -0.03 | Circular | D = 0.04 | $0^0$ |

## 3. Experimental Testing in a Wind Tunnel

Experimental efforts have been acknowledged as a proven instrument for conducting research. The turbine model of the two airfoil profiles was designed using QBlade software based on code developed using the improved BEM theory [42]. All the concise design parameters have been exhibited in Table 2. The turbine is fabricated to be tested in the Low Speed Tunnel at Universiti Teknologi Malaysia (UTM-LST). UTM-LST is a closed circuit, return-type subsonic wind tunnel with good flow quality facilities, capable of delivering high accuracy and good repeatability tests. The wind tunnel has a test section with the dimensions of 6.0m length X 2.0m wide × 1.5m high, with solid walls and a maximum wind speed of 80 m/s powered by a 430 kW AC motor. It has a 0.15% uniformity and a 0.06% turbulence intensity [37-41]. The test set-ups are shown in Figure 5-7.


**Fig. 5.** Installation of the wind turbine model inside the section testing of the UTM-LST wind tunnel for testing


**Fig. 6.** The two-airfoil turbine inside the section testing of the UTM-LST wind tunnel

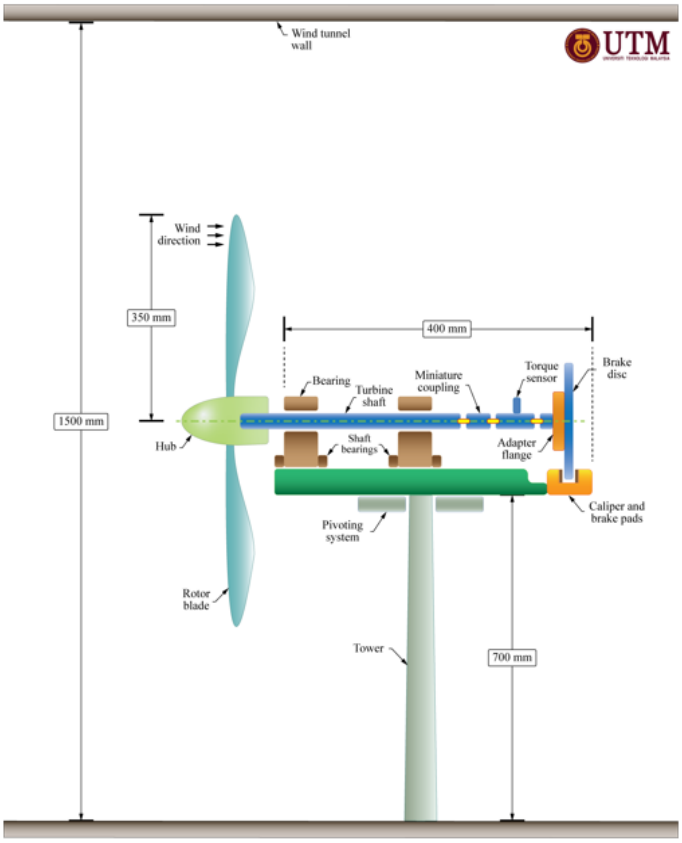


**Fig. 7.** A schematic side view illustrates the wind turbine model components

A wind tunnel is a useful tool when it comes to conducting model studies and providing a variety of reliable data to support design decisions. Designing with wind tunnels also saves time and money. A wind tunnel test section, on the other hand, has a finite size, so the flow conditions are not the same as without a boundary. Thus, wind tunnel tests must account for some effects which include horizontal buoyancy, solid blockages, wake blocks and so on [43]. As per as extensive wind tunnel testing is concern, it is necessary to consider the blockage correction. The wind tunnel total wake and solid blockage correction are given by Eq. (1) [43]. Typically, solid blockage (the ratio between the model frontal area and the test-sectional area) for solid models, such as aircraft models, should be less than 5%. However, corrections are entailed for higher blockages. This research concentrates on experimental blockage studies in wind tunnel tests of rotating rotors.

$$\varepsilon_t = \left(\frac{1}{4}\right)\frac{Model\ Frontal\ Area}{Test\ Section\ Area} \quad (1)$$

The calculation reveals 3.2% of blockage which is very small and negligible compared to the correction limit. Therefore, as per wind tunnel experimental studies is a concern, it seems that no blockage correction is required for a rotor blockage ratio as various literature articulates the maximum possible unnecessary correction limit is 10% [43-45]. The wall interference correction was also small and negligible [43].

However, as a stable, accurate, and convenient to calibrate a pitot-static tube was employed to determine the free stream velocity in this test section. An analog/digital converter was used to convert the data logger to digital dataflow, which was then saved onto a computer. (PC) as shown in Figure 8 and 9 below.

**Fig. 8.** A pitot-static tube to measure the free stream velocity


**Fig. 9.** data logger uses the analog/digit converter to digital dataflow

Furthermore, the wind tunnel testing set-up also involves the use of a Laser Light Device (LLD) GLL 2 model to ensure proper alignment during wind tunnel testing, as shown in Figure 10-12. This self-leveling crossline laser is employed to precisely align the wind turbine with the incoming wind stream. The wind turbine is mounted on a turntable that can be set to yaw angles ranging from ± 180 degrees [46]. The LLD is capable of self-leveling up to ±4 degrees with an accuracy of ± 3mm/m at a distance of 10m (top and bottom). It provides high visibility of the laser lines and has a working range of 20m. This helped guarantee accurate results during the test setup and wind tunnel testing.


**Fig. 10.** View of the Laser Light Device

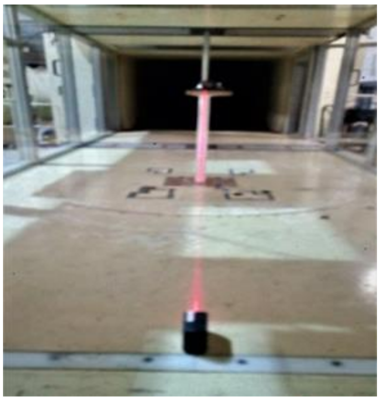

**Fig. 11.** Use of the Laser Light Device to align the model inside the section test of the wind tunnel

**Fig. 12.** Laser Light Device precisely orients the turbine rod inside the UTM-LST wind tunnel

The torque sensor, depicted in Figure 13-15, was utilized to determine the mechanical torque installed on the main shaft between the rotor blade and the brake system. This instrument, commonly found in HAWT blade systems, has been proven to accurately measure the power coefficient in various studies [26,47,49,50]. To attain the most precise results, it's crucial to position the torque sensor adjacent to the rotor blade to minimize any disruption caused by shaft friction during measurement. In this research, the torque sensor TSR605, 5 N-m, non-contact shaft-to-shaft rotary sensor w/ Encoder, 10mm Shaft, operate up to 7000 rpm, 12 Pin Binder Receptacle, utilizes strain gauge technology was calibrated to ensure accuracy, yielding Eq. (2). This equation corrected the data logger torque (Y) and the actual torque (X) readings. After verifying the measurement errors, the torque sensor was removed from the test shaft, and the calibration data were adjusted to fit the wind turbine shaft torque using the scaling factor of 2.

$$Y= 0.5053X+0.0007 \tag{2}$$


**Fig. 13.** View of the torque sensor to measure the shaft turbine torque


**Fig. 14.** Side view of the torque mete

**Fig. 15.** Calibration set-up of the torque sensor

The mechanical brake system can effectively stop the turbine by imitating the various loads on the rotor blades and managing them. A disk brake is utilized in this research model, and it functions in a similar way to those found on motorcycles or cars, as depicted in Figure 16. A steel disk is firmly attached to the shaft through an adapted coupling to the brake. When an external force is applied, the actuated caliper presses the brake pads against the disk. An effective wind turbine brake must be capable of exerting more torque than the rotor can deliver. In accordance with standards, the brake's design torque should be equal to the wind turbine's maximum design torque. The brake should start applying force almost instantly and reach full torque within a few seconds. The ramp-up time is chosen to strike a balance between being too fast (which would impose a very high temporary load on the drive train) and too slow (which could cause rotor acceleration and brake heating during deceleration). Typically, the entire braking process, from start to full stop, takes less than five seconds. The brake's energy absorption capability is crucial. Firstly, it must absorb all the kinetic energy in the rotor at its maximum speed. Furthermore, it should also absorb any extra energy the rotor might gain during stopping. [5].

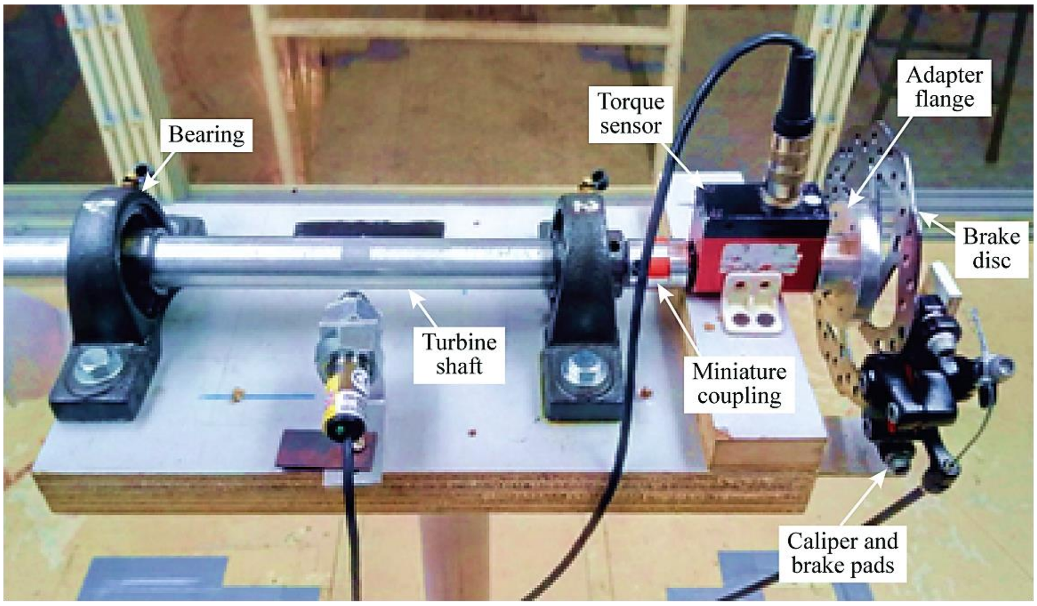


**Fig. 16.** Mechanical Brake system for Wind Turbine speed control

In this study, the rotation speed of the rotor blades was measured using a tachometer, as shown in Figure 17. A tachometer is a tool used to determine the rotation speed of a shaft or disk, such as in a motor or other machine. The device typically displays the revolutions per minute (RPM) on a calibrated analog or digital display with an optical range of 50mm-2000mm, an RPM range of 3-99,999, and an accuracy of 0.02% of reading ± 1 digit. Since wind turbines have a high rotational speed, it was necessary to measure its RPM without physical contact. Thus, a laser tachometer was the appropriate instrument for this measurement [51,52].

**Fig. 17.** Tachometer to measure the rotor blade rpm

The EN17 digital inclinometer, as showcased in Figure 18, enables the precise measurement of angles, particularly the blade pitch angle at varying free stream speeds, with a highly accurate resolution of 0.1 degrees [53]. This tool is perfect for projects that demand level alignment, and its ease of use is due to its reverse reading feature. When it comes to measuring gradients in challenging viewing conditions, the inclinometer has a handy hold button that saves the measurement, so you can easily read the display away from the work area. This study utilized the EN17 digital inclinometer to set the ideal pitch angles for the blades.


**Fig. 18.** Inclinometer to measure the blade desired pitch angle

The objectives of this test are to investigate the startup speed of the turbine as shown in Figure 6 and measure its power coefficient. The following measures were taken to determine the starting speed of these configurations

i. The brake system and the torque sensor are unplugged from the rotor shaft to reduce the static friction as low as possible.
ii. The wind speed of the wind tunnel was set to 3 m/s from static (zero speed).
iii. The wind speed was monitored using a Pitot tube. The transient speed at which the turbine started rotating was written as the startup speed.

### 4. Results and Discussion

In this investigation, the wind tunnel data were obtained in different operating conditions, such as low wind speeds and different pitch angles. In addition, the findings were compared to BEM theory data obtained using QBlade. QBlade is a well-known code for solving wind turbine aerodynamics utilizing Blade Element Momentum theory [42]. The startup speed of the new arrangement improved during the wind tunnel testing. The two-airfoil blade profiles turbine performed better than the single-airfoil and started running at a low wind speed of 1.5 m/s. Figure 19-23 demonstrate the change of the power coefficient of the turbine configurations in relation to the tip speed ratio. For instance, Figure 19 represents that the turbine at a speed of 5 m/s and, a pitch angle of 5° produced a maximum power coefficient of Cp = 0.34 at a tip speed ratio of 3.7. The performance of the two airfoils' blade turbine with 5° pitch angle was also tested at 3m/s to ensure that the turbine maintained a decent coefficient $C_p$ =0.32 at a tip speed ratio of 4.7, as reported in Figure 23. The results of this study are consistent with previous studies [54-57].

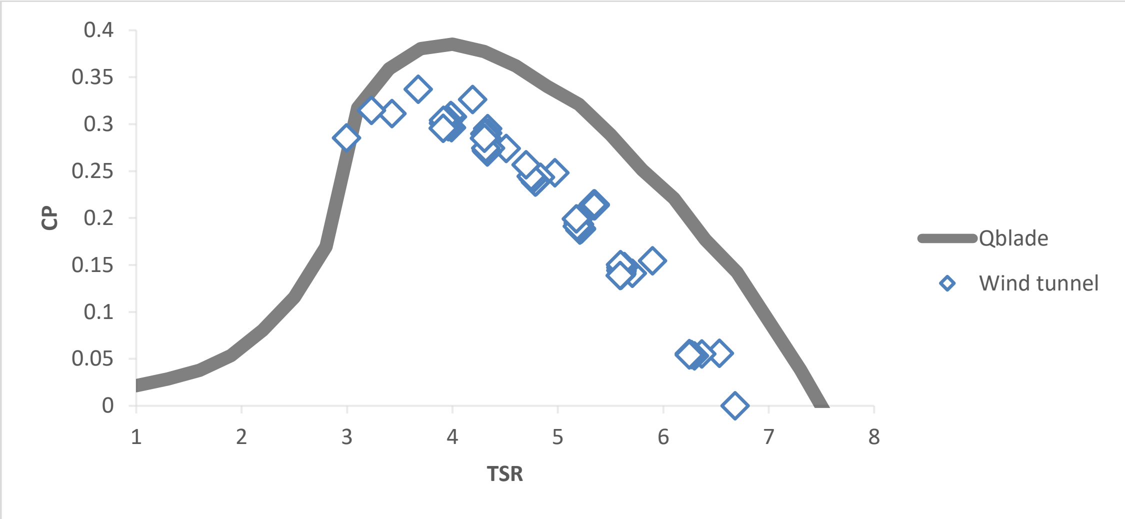


**Fig. 19.** The two-airfoil wind turbine Cp -TSR curve. (Pitch angle 5°, speed 5 m/s)

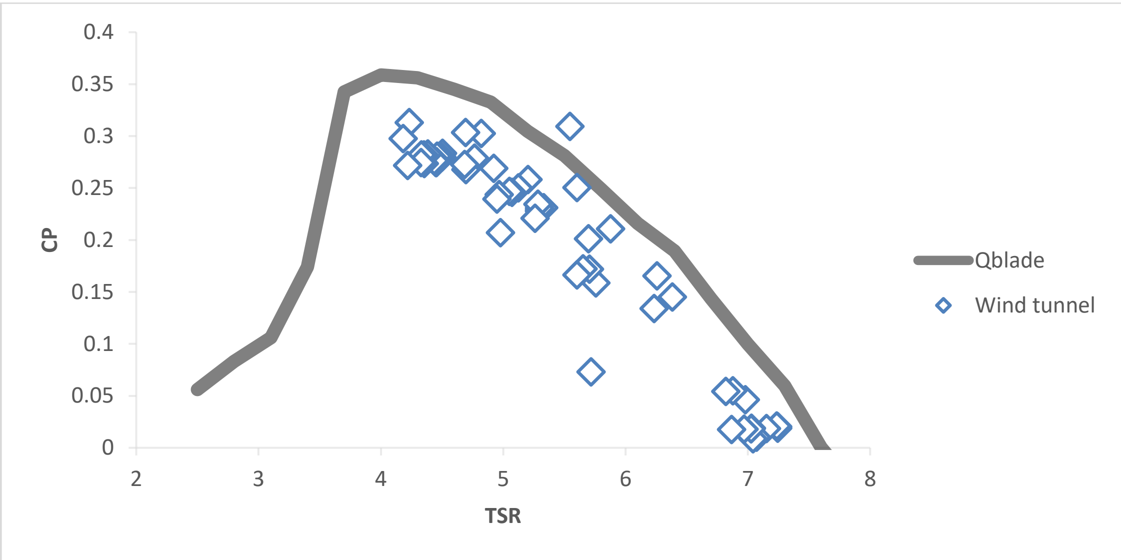


**Fig. 20.** The two-airfoil wind turbine Cp -TSR curve. (Pitch angle 0°, speed 5 m/s)

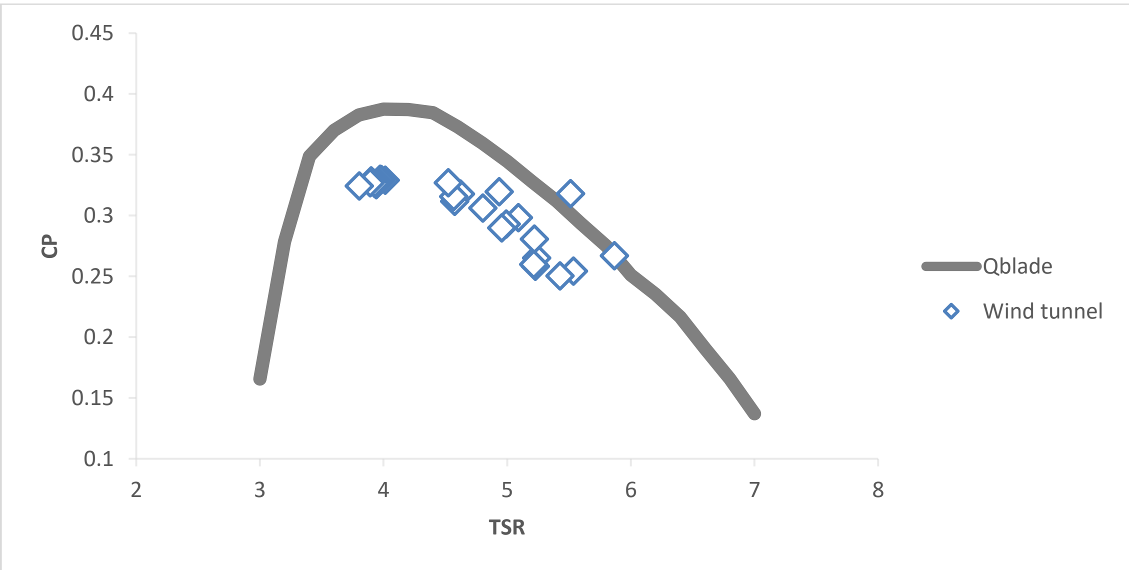


**Fig. 21.** The two-airfoil wind turbine Cp -TSR curve. (Pitch angle 3°, speed 5 m/s)

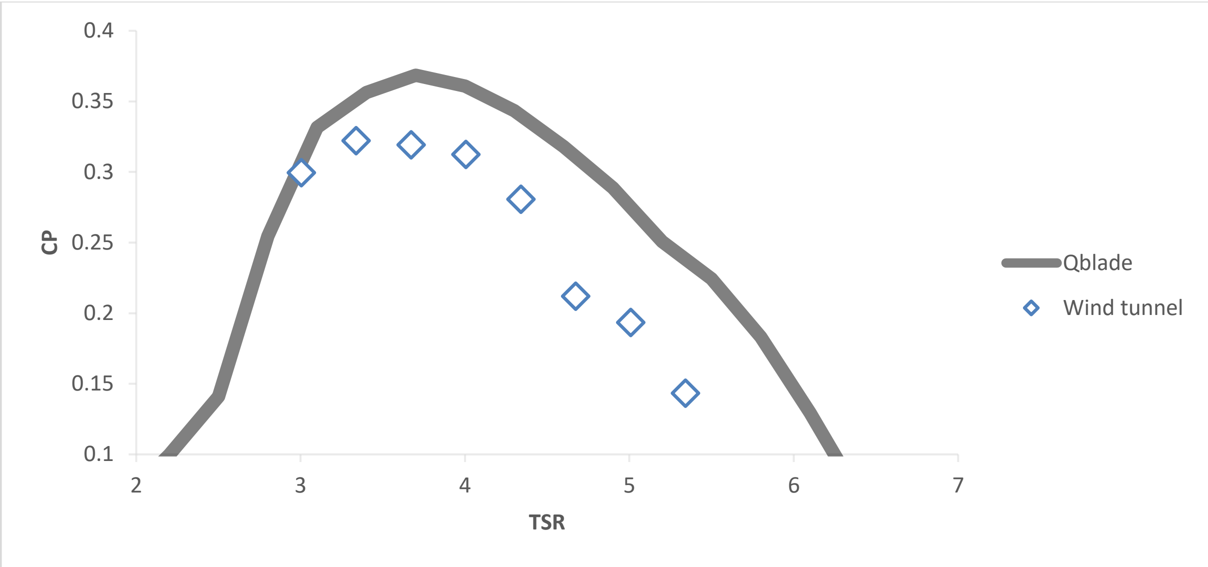


**Fig. 22.** The two-airfoil wind turbine Cp -TSR curve. (Pitch angle 7°, speed 5 m/s)

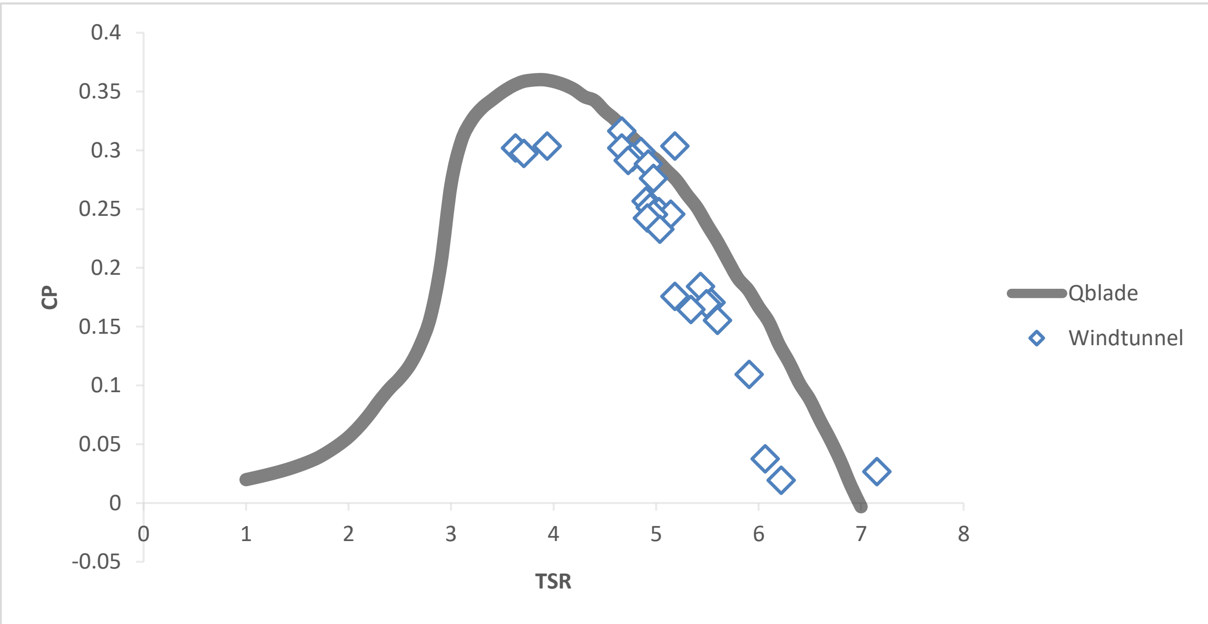


**Fig. 23.** The two-airfoil wind turbine Cp -TSR curve. (Pitch angle 5°, speed 3 m/s)

## 5. Conclusions

The experimental study on an optimized design of a small multi airfoil profiles blade with a comparatively low Reynold number ranging from $1x10^5$ to $5x10^5$ has been implemented. The QBlade software was used to design the blades using BEM theory. The results reveal that interpolated airfoils formed with SD2030 at the tip part enhance the aerodynamic performance characteristics, and with E231 at the root part can strengthen the structure and improve the aerodynamic performance of the rotor blade. However, the use of the E231 airfoil also reinforced the blade structure toward the inboard region and achieved a better start-up response at low wind speed of 1.5 m/s. The study discovered that the turbine could produce a rated power output from 0.5W to 20W with low wind speeds ranging from 1.5m/s to 7m/s and reached a maximum power coefficient of 0.34 at a pitch angle of 5° and a tip speed ratio of 3.7. The achieved results with this optimized SWT model were found significantly good power performance and were in good agreement compared with the available data and literature.

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