Chapter 3

Comparison of Power Performance of Horizontal Axis Wind Turbines with NACA 4412 and NREL S809 Airfoils

Mehmet Bakırcı[1]

Abstract

To investigate the power coefficient values, two different horizontal axis wind turbines were designed with the use of two airfoils; NACA 4412 and NREL S 809. These had three blades with a radius of 40 cm and were produced using a 3D printer. Power coefficients were calculated by measuring the torque values generated in these turbines for different tip speed ratios. The homogeneous wind obtained by a moving vehicle is used to produce artificial wind. The highest power efficiency was achieved with NACA 4412 compared to NREL S809, but the power efficiency value was higher with NREL S809 at values greater than 9 of the tip speed ratios with NACA 4412.

1. Introduction

Our world's need for energy, especially electrical energy, continues to increase day by day. Countries, especially in the last 30 years, have focused on the development of electricity generation technologies using sustainable resources like solar, wind, geothermal, biogas, tidal energy, which do not pollute the atmosphere and are not depleted. Three-blade horizontal axis wind turbines (HAWT), which are among the wind turbine types developedto utilize wind energy, have become the most preferred type due to their high efficiency [1].

The power efficiency of these turbines depends on the airfoil selected as the blade section, how these airfoils are positioned on the blade and the rotor tip speed ratio (TSR) value [2].

Studies on the parameters on which the tip speed ratio (TSR), ratio of the wing tip tangential (linear) velocity and the wind speed, depends and its optimum value are found in the literature. In general, optimum tip

[1] Karabuk University, Mechanical Engineering, mehmetbakirci@karabuk.edu.tr

https://doi.org/10.58830/ozgur.pub130.c540

speed ratio (OTSR) values ranging from 1 to 5 for multi blades, 4-10 for three blades, 9-15 for two blades and 15-20 for one blade are given [3]. For example, Bai [4] stated this value as 5, while Wang [5] stated it as 10 for three bladed ones. In this study, the tip speed ratio value at where the highest power efficiency is obtained is investigated. The second aim of this paper is to compare the power efficiencies of the HAWT designed with NACA 4412 and NREL S809 airfoils. While NACA series airfoils were used more in the past, NREL series airfoils, which were specially developed for wind turbines, were preferred [6].

Blade tip tangential speed and the wind speed in the free region (V_∞) ratio is defined as the tip speed ratio (TSR) and is denoted by λ in this paper. The blade tangential velocity U is equal to the product of the rotational angular velocity ω and the blade length R [7].

$$\lambda = \frac{\omega R}{V_\infty}$$

The power to be obtained from a wind turbine equals to the product of the rotational angular speed and the torque produced by the blades [7]. When it is desired to obtain high torque (moment), low rotational speed is generated, while low torque is generated at high rotational speeds. The product of these two values (torque and angular rotational speed) gives the power value to be obtained. For obtaining the maximum power, calculating the optimum values of the angular rotational speed or torque is important [8]. In other words, the optimum tip speed ratio (OTSR) for obtaining the maximum power coefficient (C_P) value must be determined for a HAWT.

The rotor rotates very slowly, allowing the wind to pass through the openings between the blades, so that some of the wind passing through the rotor cross-section is not utilized. But when the rotor rotates excessively fast, the blades function like a barrier blocking the passage of wind, resulting in an incomplete utilization of wind power. Therefore, a HAWT should be designed to operate at the most favorable TSR for extracting the maximum possible power from this flow of wind. The power efficiency (C_P) value of the HAWT varies according to the TSR value. While the C_P value takes small values at very low TSR values, the C_P value also increases when the TSR value is increased. However, this increase occurs up to a certain TSR value, after this value, the C_P value starts to decrease while the TSR value increases (Figure 1) [9].

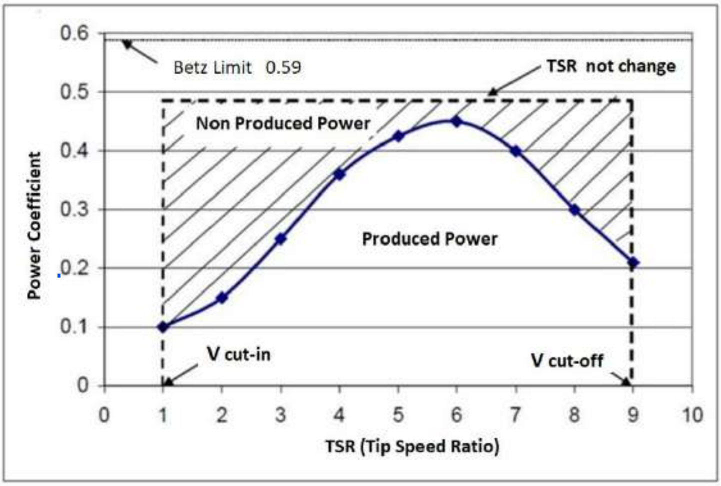

Figure 1. Power coefficient-TSR relationship [9].

M.Ragheb[10] proposed the optimum tip speed ratio's mathematical calculation in this way: For a wind turbine with horizontal axis, the time required for one of its blades to be replaced with its next one is same as the required time for the wind entering inside and being disturbed and restored after hitting it. Where B is indicated as the blade number, time for the next blade to replace it, it is calculated with the following equation;

$$t = \frac{2\pi}{B\omega}$$

The time it takes for the wind hitting the blade to regain its original state after it is disturbed t=S/V; S=the path taken by the wind hitting the blade until it regains its original state, V=wind speed. If these two times are equalized and the angular velocity is written;

$$\omega = \frac{2\pi V}{B.S}$$

The above relation is obtained. Here the value of S is based on the experimental results and is stated by Ragheb [10] to be taken as R/2. If the definition of TSR is used, the optimum tip speed ratio value (OTSR) is equal to $4\pi/B$. We observe that the optimum tip speed ratio (OTSR) value for B=3 blades is $4\pi/3$ and this value is approximately 4.19. It is stated that if the airfoil selection is made correctly, the optimum tip speed ratio value will be 25%-30% higher than this value. That is, it can be expressed as $5.24 < \lambda_{optimum} < 5.45$ [10].

An empirical formula is given in the literature [11] where the power coefficient (C_P) value can be calculated as a function of TSR (λ), blades number(B) and the maximum C_L/C_D ratio of the airfoil used in the wing section:

$$C_p = (\frac{16}{17})\lambda\left[\lambda + \frac{1.32+\left(\frac{\lambda-8}{20}\right)^2}{B^{2/3}}\right] - \frac{0.57\lambda^2}{\frac{C_L}{C_D}\left(\lambda+\frac{1}{2B}\right)}$$

In the above formula, C_P (power coefficient) and OTSR ($\lambda_{optimum}$) values found according to the maximum values of C_L/C_D ratio for HAWT having 3 blades are given in Table 1.

Table 1. C_L/C_D - $C_{p(max)}$-OTSR values according to the formula.

$(C_L/C_D)_{(max)}$	$C_{p(max)}$	OTSR
25	0.43	3.5
50	0.47	5
75	0.5	6
100	0.52	8
130	0.3	9

The higher the $(C_L/C_D)_{(max)}$ ratio that demonstrates the airfoil's aerodynamic performance, the higher the C_P value [12]. The OTSR value is also affected in the same way (Table 1). In the mentioned formula, the effects of the number of blades (B) on $C_{P(max)}$ and OTSR can also be calculated. While the effect of C_L/C_D value on $C_{P(max)}$ and OTSR is high when the number of blades is low, it is seen that this feature of the airfoil does not have much effect as the number of blades increases. However, in this formula, the effects of airfoil $(C_L)_{max}$ value, design angle of attack, Design Tip Speed Ratio (DTSR) value and dimensions of the blade geometry on $C_{P(max)}$ and OTSR are not taken into account [13].

Mc. Cosker calculated the effects of the design tip speed ratio value on the blade geometry as well as rotor aerodynamic performance of the selected airfoil in the design of a R=2.5 m long HAWT with 3 blades using the BEM theorem. As a result of his study, he obtained $C_{p(max)}=0.53$ with NACA 23012 at OTSR=7. While creating this geometry, DTSR=6 value was used. NACA 4412 airfoil obtained $C_{p(max)}=0.55$ value at OTSR=11 value. While creating this geometry, the design used the value TSR=8. Again, using these two airfoils, he calculated the effects of design TSR values on $C_{p(max)}$ and OTSR (using values 6, 7, 8 for DTSR) with the Blade Element momentum (BEM) theorem. In cases where the TSR value is less than 6, the NACA 23012 airfoil is more efficient in contrast with the NACA 4412 airfoil, while for cases where this ratio is greater than 8, the NACA 4412 is more efficient. In general, he stated that NACA 4412 is more optimum. Cosker used the airfoil C_L and C_D values from the literature [22] and $Re=6.10^6$ [14].

Raşit Ata has developed an optimum design method by calculating how the power multiplier value is affected by which parameters in the HAWTs using artificial neural network. Taking into account the airfoil C_D (drag coefficient), blade tip losses, air reverse flows in the turbine downstream, power losses due to the number of blades, the maximum power multiplier and OTSR values were calculated using the artificial neural network optimization method. For a 3-blade HAWT, $C_{P(max)=}0.4576$ value was found at OTSR=8.5 with NACA 4415 airfoil and $C_{P(max)=}0.492$ value was found at OTSR=10 with LS-1 airfoil. In the study, the effects of the number of blades and airfoil attachment angle on power performance were shown with numerical values [15].

Bai et al. used the NACA 4418 airfoil in the design of a three-winged HAWT with a 0.36 m long wing. At 10 m/s wind speed, they found the maximum $C_{P(max)}$ value to be approximately 0.43 by BEM theorem, approximately 0.42 by Computational Fluid dynamics (CFD) simulation and approximately 0.415 by experiment. These values were obtained at OTSR=4.9. They also used 5 as the design TSR value while creating the geometry. They stated that the Reynolds number affects $(C_L/C_D)_{(max)}$ the value and thus has a significant effect on $C_{P(max)}$ and OTSR values. For this reason, when calculating $C_{P(max)}$ and OTSR values with empirical formulae and BEM Theorem, it is necessary to be very careful at which Reynolds value the $(C_L/C_D)_{(max)}$ value is taken. In a graph given by Bai, it is seen that the $(C_L/C_D)_{(max)}$ value of NACA 4418 airfoil is 13 for Re=40 000, 32 for Re=70 000, 42 for Re=100 000. For very long blades, the value of Reynolds number changes significantly from the center towards to the tip. However, when the wing width is reduced from the center of the wing to the tip, it is stated that the Reynolds number will not change much since the air's relative velocity while striking airfoil will increase towards the tip while the airfoil chord length will decrease towards the tip. It has been observed in many studies in the literature that the optimum TSRvalue for HAWTs with a blade length of 10 m and more is above 7, while in the Bai study, the OTSR value for the HAWT with a length of 0.36 m was realized around 5 [16].

Han Cao analyzed the 2D aerodynamic performance of DU 93-W-210 and NREL S 809 airfoils with CFD. The air velocity was taken as 23.8 m/s and Reynolds number as 1 million. Since DU 93-W-210 aerodynamic performance is better than NREL S 809, this airfoil was used in the HAWT design. Using DU 93-W-210, he designed a 4.5 m radius LWT. He performed 3D CFD simulation to calculate the power that this wind turbine can generate. He calculated that the power that can be obtained at a wind speed of 8.8 m/s is 9518 W whilethe optimum TSR value is 8. In this CFD simulation with Ansys fluent, he calculated thatthe part of the torque value caused by pressure is 448.7 N.m and the negative torque caused by viscosity is 21.7 N.m and 427 N.m net. Improvements were made in the tip and hub geometries of the wing and CFD simulation showed an 11% improvement in power performance. While at a wind speed of 3.5 m/s as well as the rotational speed of 60 rpm, thetorque was 106 N.m and the power coefficient value was 0.42. At a wind speed of 8.8 m/s and the rotational velocity of 150 rpm, the torque value was 812 N.m and the C_P value was 0.49 [17].

Azevedo-Mendoncha, in their study in which they applied the maximum power tracking method, it is seen in the (C_P-TSR) graph that the different sizes of the HAWT have different OTSR and Cp(max) values. It is understood from the graph that $C_{P(max)}=0.2$ and OTSR=2 when R=5 cm, $C_{P(max)}=0.29$ and OTSR=3.7 when R=15 cm, $C_{P(max)}=0.4$ and OTSR=8.2 when R=40 cm. It is seen from the graphs that $C_{P(max)}$ value exceeds 0.45 and OTSR value is around 8 for the larger HAWT. For HAWTs smaller than 1 m diameter, it is understood that $C_{P(max)}$ and OTSR values are highly affected. Since it is known from other studies that these values are also affected by wind speed, it is clear that it would be more accurate to express these two parameters with Reynolds number. Reynolds number due to its determining impact on $(C_L/C_D)_{max}$ value, which is the aerodynamic property of the airfoil. It is understood from many studies in the literature such as mathematical- empirical formulas, BEM theorem, CFD simulation that $(C_L/C_D)_{max}$ value directly affects OTSR and $C_{P(max)}$ values[18].

Wang calculated the C_P values for a 83 m diameter 3-bladed HAWT with three different methods for different TSR values (3<TSR<13). These methods are as follows: 1-FVM (free vortex method), 2-Computational fluid dynamics (CFD), 3-Wind tunnel experiment. While the FVM method found the $C_{P(max)}$ value as 0.53 at OTSR=10, the CFD simulation found the $C_{P(max)}$ value as 0.51 at OTSR=9.5 and the wind tunnel experiment found the $C_{p(max)}$ value as 0.5 at OTSR=10 [19].

Padmanabhan-Saravanan compared the performance of NACA and NREL airfoils with R=2.5 m radius and 3 blades: While $C_{P(max)}$ value of 0.52 was obtained with NACA at TSR=10, $C_{P(max)}$ value of 0.49 was obtained with NREL airfoil at TSR=10. However, while $C_{P(max)}$ values close to each other were obtained with both airfoils at TSR values less than 10, higher C_P values were obtained with NREL at TSR values greater than 12. Although NACA has a higher $C_{P(max)}$ value, they concluded that NREL airfoil is more efficient for a wider range of values of TSR [20].

In this study, the power efficiencies at different angular rotational speeds of two different horizontal-axis wind turbines designed using two airfoils selected from NACA and NREL series were experimentally measured.

2. Materials and Methods

There are different types of experiments to measure the aerodynamic performance of wind turbines [21]; such as experiments in the wind tunnel, long-term open field tests in naturalwind environment, turbine test in the face of artificial wind generating fan, experiment mounted on a pick-up truck. In the wind tunnel, there are difficulties in providing the desired dimensions of the ratio of turbine size and duct cross-section size (for accurate measurements, it should be at most 1/5 [21]. There are difficulties in obtaining homogeneous wind in the study of creating artificial wind with a fan and conducting experiments. In natural wind environment, it is not always possible to obtain constant speed wind [21]. In this study, in order to provide homogeneous and constant speed wind flow, a 40 cm long HAWT experiment with 3 blades mounted on a car was carried out (Figure 2).

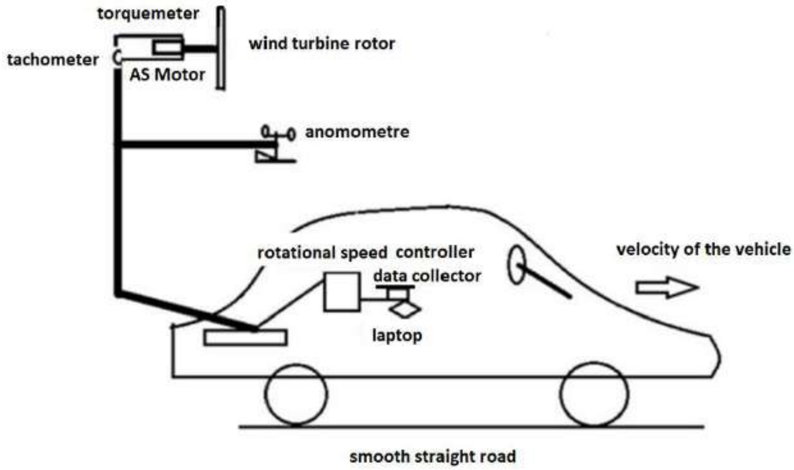

Figure 2. Experimental setup.

A 40 cm blade-length, three-bladed HAWT was designed according to the Schmitz equations with NACA 4412 [23], and NREL S 809 [24]. Schmitz equations;

$$c(r)=\frac{16\pi r}{B(C_L)_T}\sin^2\left(\frac{1}{3}\arctan\left(\frac{R}{r\lambda_T}\right)\right)$$

$$\beta(r)=\frac{2}{3}\arctan\left[\frac{R}{r}\frac{1}{\lambda_T}\right]-\alpha_T$$

c(r): airfoil length.

r: distance from the rotor center.

B: number of blades.

$(C_L)_D$: airfoil design lift coefficient value

R: blade length (rotor radius)

β(r): airfoil pitching angle

α_D : airfoil design angle of attack

λ_D : design tip speed ratio

NACA 4412 and NREL S 809 airfoils are shown in Figure 3 and Figure 4. The designed blades were produced with a three-dimensional printer (Figure 5).

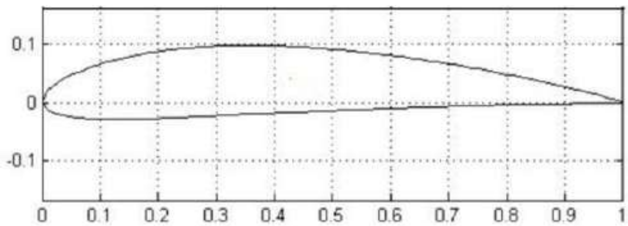

Figure 3. NACA 4412 cross section [23].

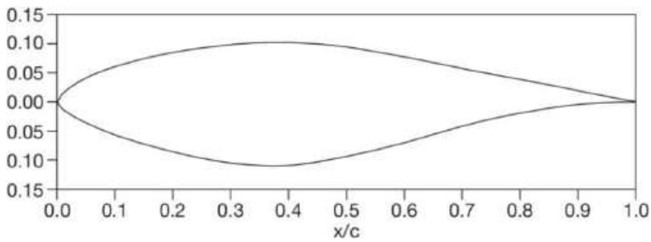

Figure 4. Cross section of NREL S809 [24].

The NACA 4412 airfoil has a maximum lift coefficient of 1.4, whereas the NREL S809 airfoil has a maximum lift coefficient of 1.3. This means that the NACA 4412 airfoil can generate more lift than the NREL S809 airfoil. The NREL S809 airfoil has a lower drag coefficient than the NACA 4412 airfoil at low angles of attack. However, at higher angles of attack, the NACA 4412 airfoil has a lower drag coefficient than the NREL S809 airfoil. The NACA 4412 airfoil has a sharp stall, meaning that it experiences a sudden drop in lift when it reaches its maximum lift coefficient. In contrast, the NREL S809 airfoil has a more gradual stall, which means that it can maintain lift at higher angles of attack before experiencing a drop in lift. both airfoils have different design characteristics that make them suitable for different applications. The NACA 4412 airfoil is better suited for low-speed applications, while the NREL S809 airfoil is designed for higher-speed applications, particularly in wind turbines.

The C_L and C_D values for the NREL S809 airfoil are taken from Sorensen ([24], while these values for the NACA 4412 airfoil are taken from Abbot [23]. When these values are used for NACA 4412; the design

AOA is 6º where the maximum value of C_L /C_D is obtained. The C_L value at this angle of attack (AOA) is 1.04. Similarly, for NREL S809, the design angle of attack (DAOA) is 5º while the design lift coefficient value is 0.76. The design tip speed ratio value was taken as 7, based on the study of Cosker [14].

Figure 5. HAWT picture produced by three-dimensional printer.

The turbine was mounted on the car as shown in Figure 2 and a system was installed to measure wind speed, wind direction, rotational speed and torque 5 times per second to ensure homogeneous airflow. The rotational speed was controlled by an electronic control system that braked the AS motor. The circuit diagram is shown in Figure 6. The vehicle was driven on a flat smooth road at a constant speed between 16 km/h and 54 km/h. The data obtained were analyzed with Microsoft Excel software.

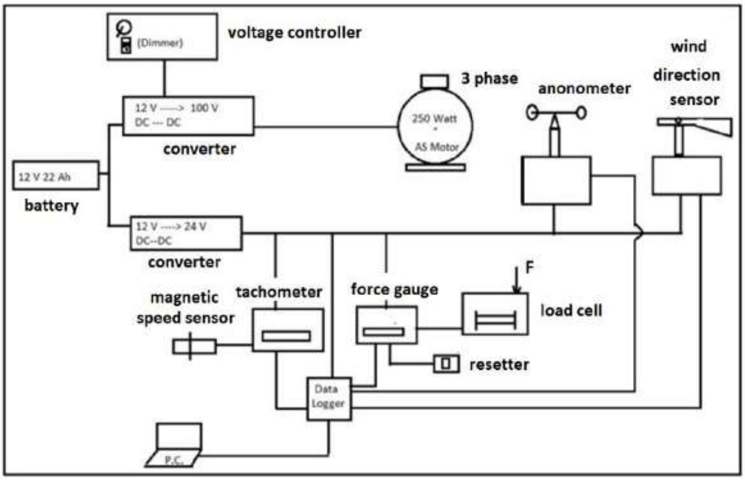

Figure 6. Circuit diagram of the experimental measurement system.

The pictures of the measuring instruments used in the experiment to measure the wind speed, rotor rotational speed (by number of revolutions) and torque (moment) values are shown in Figure 7. The blades rotating at a certain wind speed were braked by the AS motor to rotate at different angular speeds. For the torque values at different rotational speeds, the force values were first measured with a load cell. The measured force values were multiplied by the distance of 0.15 m, which is the length of the force arm in the system, and moment values were obtained.

Figure 7. Experimental measurement devices.

Wind speed was measured with an anemometer, the number of revolutions of the blades with a tachometer and torque values with a force gauge at different rotational speeds. The values found were recorded in the excel program on the computer with a data logger. The values recorded with the data logger were calibrated to convert volt values into numerical data and recorded on a laptop computer. Wind speed, wind direction, rotor speed and torque (momentum) values were recorded 5 times every second. In order to change the number of revolutions, braking was provided with AS motor. Based on the values measured at different times, torque values were measured at different speeds for cases where the wind speed was 6 m/s. TSR values were obtained using these values and angular velocity, speed and wind speed. For each different TSR values, the power was obtained by multiplying the torque value by the angular velocity ω. C_P power multiplier value was obtained by dividing the power values by the maximum power value. C_P-TSR values Table 2 and Table 3 was created for NACA 4412 and NREL S809 HAWT. $C_{P(max)}$ as well as OTSR values have been determined from this table.

3. Results and Discussions

The product of the torque (Nm) measured in the experiment and the angular rotational speed ω (rad/s) gives the power value (Watt). The maximum power of the wind flowing across the rotor section can be calculated by below equation;

$$P = \frac{1}{2}\rho V^3 \pi R^2$$

In this equation, the maximum power value of the air flowing across the turbine rotor section is calculated as 65.1 Watt when the air density ρ = 1.2 kg/m³, V wind speed 6 m/sand R = 0.4 m. The power value obtained at the rotor is calculated as torque (T) Nm and angular velocity (ω) rad/s. Power obtained is calculated by using following equation;

$$P = T.\omega$$

Two HAWT vehicles with NACA 4412 and NREL S809 sections were measured at different rotational speeds and torque values by providing homogeneous wind. The number of revolutions per second is obtained by dividing the number of revolutions per minute by 60 and the angular velocity ω (rad/s) value is obtained by multiplying this number by 2π, and the wing tip tangential velocity is found by multiplying the ω value with R

= 0.4 m. The TSR (λ) value is calculated by dividing the wing tip tangential speed by the wind velocity V=6 m/s. The results obtained as a result of the measurement values and calculations are given in Table 2 and Table 3.

Table 2. NACA 4412 measured values

Number of revolutions (rpm)	ω (rad/s)	TSR(λ)	Torque (N.m)	Power(watt)
573	60.00	4	0.282	16.92
717	75.08	5	0.260	19.52
860	90.06	6	0.253	22.78
1003	105.03	7	0.248	26.05
1147	120.11	8	0.238	28.59
1290	135.09	9	0.173	23.37
1433	150.06	10	0.117	17.56
1576	165.04	11	0.071	11.72
1720	180.12	12	0.0325	5.85
1863	195.09	13	0.0267	5.21
2006	210.07	14	0.0217	4.56

With NACA 4412 HAWT, the maximum power was measured as 28.59 Watt at a rotationalspeed of 1147 rpm (ω=120.11 rad/s). As the TSR values increase from 4 to 8, the powervalue obtained also increases, but the power value starts to decrease after 8. The OTSR value of the HAWT designed with NACA 4412 and DTSR=7 was 8.

Table 3. NREL S809 measured values

Number of revolutions (rpm)	ω (rad/s)	TSR(λ)	Torque (N.m)	Power (Watt)
573	60.00	4	0.270	16.20
717	75.08	5	0.243	18.25
860	90.06	6	0.224	20.17
1003	105.03	7	0.211	22.16
1147	120.11	8	0.200	24.02
1290	135.09	9	0.188	25.40
1433	150.06	10	0.147	22.06
1576	165.04	11	0.130	21.45
1720	180.12	12	0.112	20.17
1863	195.09	13	0.067	13.07
2006	210.07	14	0.046	9.66

With NREL S809 HAWT, the maximum power was measured as 25.4 Watt at a rotational speed of 1290 rpm (ω=135.09 rad/s). As the TSR values increase from 4 to 9, the power value obtained also increases, but the power value starts to decrease after 9. The OTSR value of the HAWT. When the stance angle of the blade to the rotor is adjusted to facilitatethe first movement, the maximum rotational speed is lower than in the other case.

designed with NREL S809 and DTSR=7 was 9. However, in order to see the different results in the values obtained due to the effect of the road surface, slight differences in vehicle speed and errors in the measurements, measurements were made with 5 different experimental studies for both HAWT. After organizing the obtained data as given in Table 5 and Table 6, the power efficiency (C_P) values were calculated using the below equation. To calculate the rotor power efficiency value, below equation is used.

$$C_P = \frac{P}{\frac{1}{2}\rho A V^3}$$

C_P-TSR values and average values obtained in 5 separate experiments (E1, E2, E3, E4, E5) for the NACA 4412 cross-sectioned HAWT are shown in Table 4 and graphically in Figure 8.

Table 4. NACA 4412 Cp-TSR values

NACA 4412 C_P-TSR EXPERIMENTAL						
TSR	E1	E2	E3	E4	E5	Mean Values
4	0.25	0.24	0.26	0.3	0.27	0.264
5	0.3	0.34	0.32	0.28	0.33	0.314
6	0.32	0.31	0.34	0.37	0.39	0.346
7	0.45	0.41	0.39	0.42	0.4	0.414
8	0.47	0.42	0.43	0.46	0.42	0.44
9	0.39	0.37	0.36	0.42	0.43	0.394
10	0.24	0.29	0.28	0.25	0.32	0.276
11	0.17	0.15	0.17	0.19	0.22	0.18
12	0.13	0.06	0.08	0.1	0.12	0.098
13	0.08	0.06	0.11	0.1	0.07	0.084
14	0.05	0.09	0.06	0.04	0.08	0.064

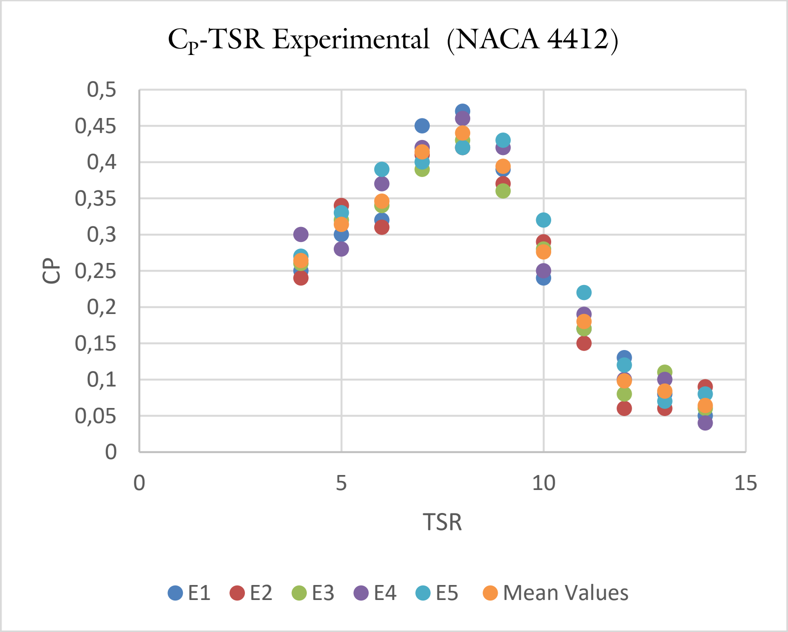

Figure 8. C_P-TSR(λ) values of NACA 4412 sectioned HAWT

Similarly, the C_P-TSR values and average values obtained in 5 separate experiments (E1, E2, E3, E4, E5) for NREL S809 cross-sectioned HAWT are shown in Table 5 and graphically in Figure 9.

Table 5. NREL S809 C_P-TSR(λ) values

NREL S809 C_P-TSR(λ) EXPERIMENTAL						
TSR	E1	E2	E3	E4	E5	Mean Values
4	0.22	0.25	0.24	0.25	0.27	0.246
5	0.29	0.28	0.25	0.28	0.25	0.27
6	0.33	0.29	0.32	0.31	0.33	0.316
7	0.35	0.33	0.34	0.34	0.3	0.332
8	0.34	0.36	0.37	0.36	0.35	0.356
9	0.34	0.39	0.38	0.36	0.35	0.364
10	0.33	0.34	0.34	0.35	0.36	0.344
11	0.34	0.33	0.33	0.3	0.32	0.324
12	0.26	0.25	0.31	0.3	0.33	0.29
13	0.18	0.22	0.2	0.21	0.22	0.206
14	0.17	0.16	0.15	0.15	0.13	0.152

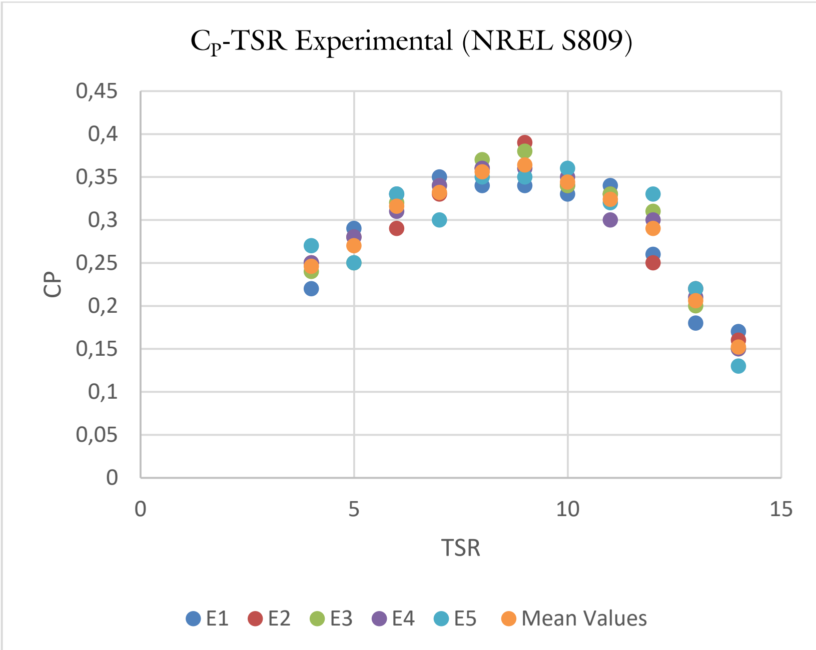

Figure 9. Cp-TSR(λ) values of NREL S809 sectioned HAWT

The graph given in Table 6 and Figure 10 is obtained according to the results obtained by averaging the C_P values of the HAWTs with both cross-sections obtained in experiments E1, E2, E3, E4, E5.

Table 6. NACA 4412 and NREL S809 Cp-TSR(λ) values

C_P-TSR(λ)	NACA	NREL
TSR	Mean Values	
4	0.264	0.246
5	0.314	0.27
6	0.346	0.316
7	0.414	0.332
8	0.44	0.356
9	0.394	0.364
10	0.276	0.344
11	0.18	0.324
12	0.098	0.29
13	0.084	0.206
14	0.064	0.152

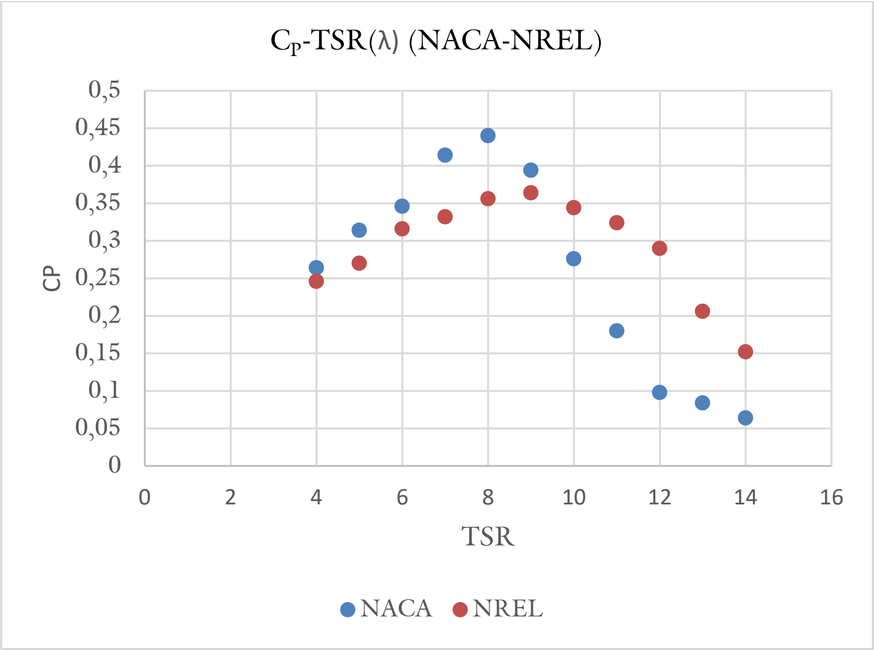

Figure 10. Compare NACA 4412 and NREL S809 HAWT C_P-TSR(λ).

According to the C_P-TSR graph obtained here, it is seen that although the performances of both are close to each other at TSR(λ) values less than 7, higher power efficiency is obtained with NACA 4412. While the highest power efficiency value was 0.44 with NACA 4412, this value was only 0.364 with NREL S809. However, at TSR(λ) values greater than 9, the values obtained with NREL S809 are larger. This situation is more clearly seen in Figure 10. The result obtained in this study may be because of the horizontal axis wind turbine blade root region stall and centrifugal pumping of flow on the blade [3].

Another situation noticed in this experimental study is that when the stance angle of the blade relative to the rotor is adjusted so that the maximum rotational speed is high, the first movement starts later. When the stance angle of the blade to the rotor is adjusted to facilitate the first movement, the maximum rotational speed is lower than in the other case.

4. Conclusion

In the experimental studies, it was observed that when the angle of the blade with the rotor plane was slightly increased, the initial movement started more easily, but it caused lower values in terms of obtaining maximum torque. A higher maximum power multiplier value was obtained with NACA 4412. However, higher power multiplier values were obtained with NREL S809 at TSR values greater than 9. As a result of the experimental study for NACA 4412 HAWT, the OTSR value was measured as 8. With NREL S809, the OTSR value was obtained as 9.

The experimental method used in this study is not a commonly used method for studying wind turbine performance. In order to obtain more reliable or accurate results, those methods such as field measurements, wind tunnel testing, or numerical simulations using validated models may be used to determine the power performance of horizontal axis wind turbines. We should say here that the method used in this study is very successful in terms of obtaining steady and uniform artificial wind, as well as many weak aspects.

To compare the power performance of two different horizontal axis wind turbines (HAWTs) with different airfoils, an experimental setup can be created in a wind tunnel. The following steps can be followed for this experiment:

1. Design and build two identical HAWTs, with the only difference being the airfoil shape. It is important to ensure that the two turbines have the same blade length, number of blades, pitch angle, and rotor diameter to ensure a fair comparison.

2. Install the two turbines in a wind tunnel, which provides a controlled environment with a steady and uniform wind flow. The wind tunnel should have a velocity range that is appropriate for the size of the turbines and airfoils being tested.

3. Connect each turbine to a power meter or dynamometer that can measure the torque of the turbine. Start the wind tunnel and adjust the wind velocity to the desired level. It is important to ensure that the wind velocity is steady and uniform across the test section of the wind tunnel.

4. Run the experiment for a predetermined amount of time, allowing the turbines to reach a steady-state condition. This will ensure that the power output measurements are accurate and repeatable.

5. Repeat this experiment at the different rotational speed of the rotor. Record the power output measurements for both turbines, and compare the results.

6. The airfoil that produces the higher power output at a given wind velocity or at a given tip speed ratio is considered to have better power performance. Repeat the experiment multiple times to ensure the reliability and repeatability of the results.

References

[1] Spera. D.A. "Wind Turbine Technology second ed.", ASME Press. New York (2009).

[2] Hau. E. "Wind Turbines Fundamentals, Technologies, Application", Economics second ed. Trans: H.Von Renouard. Springer. Hardcover (2005).

[3] Hansen. M. O. L. "Aerodynamics of Wind Turbines", 2nd ed. Earthscan. London. Sterling. VA. USA. 7-78 (2008).

[4] Bai. C. J. Hsiao. F. B. Li. M. H. Huang. G. Y. and Chen. Y. J. "Design of 10 kW horizontal-axis wind turbine (HAWT) blade and aerodynamic investigation using numerical simulation", 7th Asian-Pacific Conference on Aerospace Technology and Science. 7th APCATS (2013).

[5] Wang. T. Wang. L. Zhong. W. Xu. B. and Chen. L. "Large-scale wind turbine bladedesign and aerodynamic analysis", Chinese Science Bulletin (2012).

[6] Tangler. J. L. and Somers. D.M. "NREL airfoil families for HAWT's", Proc. WINDPOWER'95. Washington D.C. 117-123 (1995).

[7] Gundoft. S. "Wind Turbines", University Collage of Aarhus Denmark. Copyright (2009).

[8] Burton. T. Jenkins N. Sharpe D. Bossanyi. E. "Wind Energy Handbook". 2nd ed. John Wiley & Sons. Ltd. England. 41-184 (2011).

[9] Manwell J.F. Mc. Gowan. J.G. Rogers. A.L. "Wind energy explained; theory, design andapplication" 2nd ed.". John Wiley and Sons Ltd. publication. Chichester. 90-141 (2009).

[10] Ragheb. M. "Optimal Rotor Tip Speed Ratio" USA University of Illinois at Urbana-Champaign (2014).

[11] Diveux. T. Sebastian. P. Bernard. D. and Puiggali. J. R. "Horizontal axis wind turbine systems: Optimization using genetic algorithms." Wind Energy. 4(4): 151-171 (2002). [1]

[12] Anderson John D. "Fundementals of Aerodynamics", Third Edition, McGraw-Hill Book Company. New York. USA. 331-332 (2001).

[13] Gash. R. Twele J. "Wind power plans. Fundamentals, design, construction and operation", James and Janes, (2005).

[14] Cosker. Mc. J.. "Design and optimization of a small wind turbine", Requirements for MSc of mechanical engineering, Master's Thesis. Rensselaer Polytechnic Institute Hartford. Connecticut. USA (2012).

[15] Rashid. A. "An adaptive neuro-fuzzy inference system approach for prediction of power factor in wind turbines", Journal of Electrical & Electronics Engineering. 9(1): 905 -912. (2009).

[16] Bai. C. J. Hsiao. F. B. Li. M. H. Huang. G. Y. and Chen. Y. J. "Design of 10 kW horizontal-axis wind turbine (HAWT) blade and aerodynamic investigation using numerical simulation", 7th Asian-Pacific Conference on Aerospace Technology and Science. 7th APCATS (2013).

[17] Cao. H. "Aerodynamics analysis of small horizontal axis wind turbine blades by using 2D and 3D CFD modelling", Requirements for MSc of The School of Computing, Master's Thesis, Engineering and Physical Sciences, University of Central Lancashire. England (2011).

[18] Azevedo. J. and Mendoncha F. "Small Scale Wind Energy Harvesting with Maximum Power Tracking Funchal", Portugal Centre for Exact Science and Engineering, University of Madeira (2015).

[19] Wang. T. Wang. L. Zhong. W. Xu. B. and Chen. L. "Large-scale wind turbine blade design and aerodynamic analysis", Chinese Science Bulletin (2012).

[20] Padmanabhan. K. K. and Saravanan. R., "Study of the performance and robustness of NREL and NACA blade for wind turbine applications", European Journal of Scientific Research 440-6 (2012).

[21] Boorsma. K. Schepers. J. "Description of experimental setup MEXICO measurements", Technical Report, ECN-X09-0XX; ECN: Petten. The Netherlands (2003).

[22] Burton.T.. Jenkins. N. Sharpe. D. Bossanyi. E. "Wind Energy Handbook", second ed.John Wiley and Sons. Ltd. Chichester (2011).

[23] Abbot. I. H. Von D. A. E. "Theory of wing sections including a summary of airfoildata" New York, Dover publication (1959).

[24] Bertagnolio. F. Sorensen. N. Johansen. J. Fuglsang. P. "Wind turbine airfoil catalogue", Riso National Laboratory, Roskilde (2001).

[25] Internet: UIUC Airfoil Coordinates Database

[26] http:/aerospace.illinois.edu/mselig/ads/coord_database.html (2016).

[27] Pope, A. and Burton, D. "Wind Tunnel Testing for Buildings and Other Structures", John Wiley & Sons, Chichester, (1999).

[28] Burton, T., Sharpe, D., Jenkins, N., and Bossanyi, E., "Wind Energy Handbook", 2nd Edition. Wiley, Chichester, (2011).

[29] Snel, H., Schepers, J.G., and Montgomerie, B. "Wind turbine rotor aerodynamics and aeroelasticity – a simulation approach", Journal of Wind Engineering and Industrial Aerodynamics, 90(8), 923-939. (2002).

[30] Sørensen, N.N. and Mygind, L. "Airfoils for Wind Turbine Applications", Risø National Laboratory, Roskilde, (2001).