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EXPERIMENTAL STUDY AND OPTIMIZATION OF A 2.44 METER VERTICAL AXIS WIND TURBINE

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ABSTRACT

Vertical axis wind turbines (VAWTs) have long been considered a viable source for alternative energy; however, limited published research has contributed to limited technological advancement in these machines. Slower advancements are due, in part, to their complex aerodynamic models which include wake effects, vortex shedding, and cyclical blade angles of attack and Reynolds numbers. VAWTs are believed to hold several advantages over their more popular and better studied horizontal axis counterparts, including a simpler design and better efficiencies in lower wind speeds. They may have a unique niche in standalone applications at moderate wind speeds such as on an island, a remote military installation, or an inland farm. Currently, no published design standards or criteria exist for optimizing the physical properties of these turbines to maximize power output. A 2.44 m tall VAWT prototype with variable physical parameters was constructed for wind tunnel testing. The purpose of the experiment was to maximize the turbine's power output by optimizing its physical configuration within the given parameters. These parameters included rotor radius, blade chord length, and pitch offset angle. The prototype was designed as a scaled-down model of a potential future VAWT unit that may be used to sustain a small farm or 2-4 houses. The wind tunnel consisted of a 2.74 m by 1.52 m cross section and could produce maximum wind speeds of 3.56 m/s. The turbine prototype consisted of three sets of interchangeable blades featuring two airfoils of varying chord length. Spokes of varying length allowed for rotor radii of 190.5, 317.5, and 444.5 mm. The pitch offset of the blades was varied from 0°-20° with a focus on the 10°-16° range as preliminary results suggested that this was the optimal range for this turbine. Ramp-up and steady-state rotational speeds were recorded as the blades were interchanged and the turbine radius was varied. A disk brake provided braking torque so that power coefficients could be estimated. This study successfully optimized the turbine's power output within the given set of test parameters. The importance of finding an appropriate aspect ratio and pitch offset angle are clearly demonstrated in the results. A systematic approach to small scale wind tunnel testing prior to implementation is presented in this paper.

1. INTRODUCTION

Wind turbines can be categorized in two primary categories: horizontal axis wind turbines (HAWTs) and VAWTs. In most typical cases, a HAWT's blades rotate about an axis that runs parallel to the ground, whereas a VAWT's blades rotate about an axis normal to the ground. HAWTs account for the vast majority of wind turbines in the United States. They are most commonly placed together in grids, or "farms," located in high wind speed areas such as offshore or along mountainsides. Single HAWT units produce power in the range of 1-5 MW. VAWTs are usually much smaller, both in stature and power production, and are designed for lower wind speeds. They are normally stand-alone units placed in localized areas of moderate wind speed. The power output of VAWTs is typically on the scale of a few hundred kW.

Vertical axis wind turbines have a number of advantages over larger horizontal axis turbines. Perhaps the most notable advantage is the ground-level positioning of generators and primary bearings, allowing for easier maintenance. HAWT blades typically rotate at lower speeds, requiring gearboxes in most cases to increase speed for electricity generation. These gearboxes are the biggest causes of maintenance down-time and turbine efficiency loss [1]. Large scale, direct-drive horizontal turbines have recently been introduced to the market. VAWTs operate at higher rotational speeds and are usually connected directly to a generator reducing mechanical complexity. These turbines accept winds from all directions and do not require a yaw mechanism. Their efficiency curves generally peak at lower wind speeds than HAWTs, making them a more viable option for small wind.

VAWTs also have a number of disadvantages. Although a lack of yaw mechanism gives VAWTs a simpler design, their position relative to the wind is never idealized, thus these turbines have lower capacity factors. Vertical turbines also have very low self-starting torques. The fluid dynamic interaction between the incoming air and rotor is much more complicated than that of a HAWT. Wake effects and vortex shedding off of the blades and supporting structure disrupt the flight path of the blades. Not only does this decrease the efficiency of the turbine, but it makes VAWTs extremely difficult to accurately model using CFD software. Because of the aerodynamic complexity of these turbines and the known capabilities of horizontal turbines, little improvement has been made in VAWTs in the past few decades. There is little experimental data, a lack of technological advancement, and no published design criteria for these types of turbines.

A number VAWTs have been built and tested over the past few decades. Partially due to a lack of design standards, these turbines vary vastly in description and are hard to compare directly. Pinson Energy Corporation tested a vertical axis turbine named the “Cycloturbine” [2]. The turbine consisted of three straight, vertical blades 2.4 meters in length and had a diameter of 3.6 m. A NACA0015 airfoil was used. A cam device mounted to the shaft allowed the blades to passively vary their pitch offset based on wind speed and azimuth angle. Drees [2] claimed that this design allowed for self-starting in low wind speeds. Rotational speed and wind speed were measured simultaneously in an outdoor environment. A resistive load was used to measure electrical output. A maximum power coefficient of 0.45 was found at a tip speed ratio (TSR) of 3.5.

Howell et al. [3] published the results of an experimental and computational study of a small VAWT with a height of 400 mm and a diameter of 600 mm. A NACA0022 airfoil was tested with a chord length of 100 mm. The turbine was tested in a wind tunnel with a square cross-sectional test area of 1.44 m^2. The parameters varied included the number of blades, or solidity, and blade surface finish. Torque was measured using a simple brake with a known force applied by two spring balances. Rotational speed was measured once per revolution via an optical tachometer. Power and torque curves for two and three bladed rotors were presented as a function of TSR at a given incoming wind velocity of 5.07 m/s. Performance coefficient curves were presented for a number of wind speeds for both “rough” and “smooth” surfaced blades. The three bladed, higher solidity, turbine outperformed the two bladed model. Also, the performance due to surface finish was found to be dependent on wind speed with smoother blades performing better in higher wind speeds and rougher blades performing better at lower wind speeds.

Hill et al. [4] reported on a small vertical axis wind turbine model used to investigate self-starting behavior. This turbine featured a height of 0.6 m and a diameter of 0.75 m. The blades featured a NACA0018 airfoil of chord length 0.083 m. The turbine was tested in a ¾ open jet configuration wind tunnel at a wind speed of 6 m/s. The rotor was mounted directly to a 3-phase permanent magnet, axial-flux generator rated at 200 W. A graph was presented illustrating turbine ramp-up with TSR plotted over time. To obtain this plot, the turbine was held stationary until the desired wind speed had been reached and then it was released. It was observed that the turbine was able to self-start from a number of randomly chosen starting positions.

Table 1 presents a summary of three VAWTs tested and reported in previous literature. Experimental studies of scaled VAWTs are very sparse in the current body of literature. Most studies report TSRs and power coefficients for a given turbine, but fail to explain how the turbine’s physical properties were chosen. Howell et al. [3] presented a study in which the turbine properties of blade number and blade surface finish were incrementally varied. The following study expands upon this method of incremental change to provide some guidelines for choosing certain physical properties of a VAWT.

Table 1. VAWT properties in literature

Property	***Drees[2]***	***Howell et al.[3]***	***Hill et al.[4]***
NACA	0015	0022	0018
Chord (m)	0.29	0.10	0.083
Pitch Offset	Variable	Unknown	Unknown
Dia. (m)	3.6	0.60	0.75
Height (m)	2.4	0.40	0.60
AR	8.3	4.0	7.2
Solidity	0.24	0.33-0.50	0.33

It is well known that the overall theoretical limit for a wind turbine coefficient of power for wind turbines is 0.59 [5]. The theoretical limit for the power coefficient of power for a VAWT of Darrieus turbine is 0.40 at a TSR of approximately 4.5 [5, Fig. 5.10] to provide useful comparisons to this study.

In the current work, results are presented for a 2.44 m tall vertical axis wind turbine with varying rotor radius and pitch offset angle. Three airfoils were considered.

2. NOMENCLATURE

A_f – turbine projected area, m^2

D – disc brake outside diameter, mm
D_t – turbine diameter, mm
N – normal force, N
P – power, W
R_t – turbine radius, mm
Re – Reynolds number
T – torque, N/m
TSR –tip speed ratio
V_∞ - free stream velocity, m/s
c – chord length, mm
d – brake disc inside diameter, mm
n – number of blades
Ω – rotational speed, rad/s
α - blade angle of attack, degrees
μ – coefficient of friction
μ_a – dynamic viscosity of air
σ – solidity ratio, nc/D_t
ρ_a – density of air, standard conditions, 1 kg/m^3

3. EXPERIMENTAL APPROACH

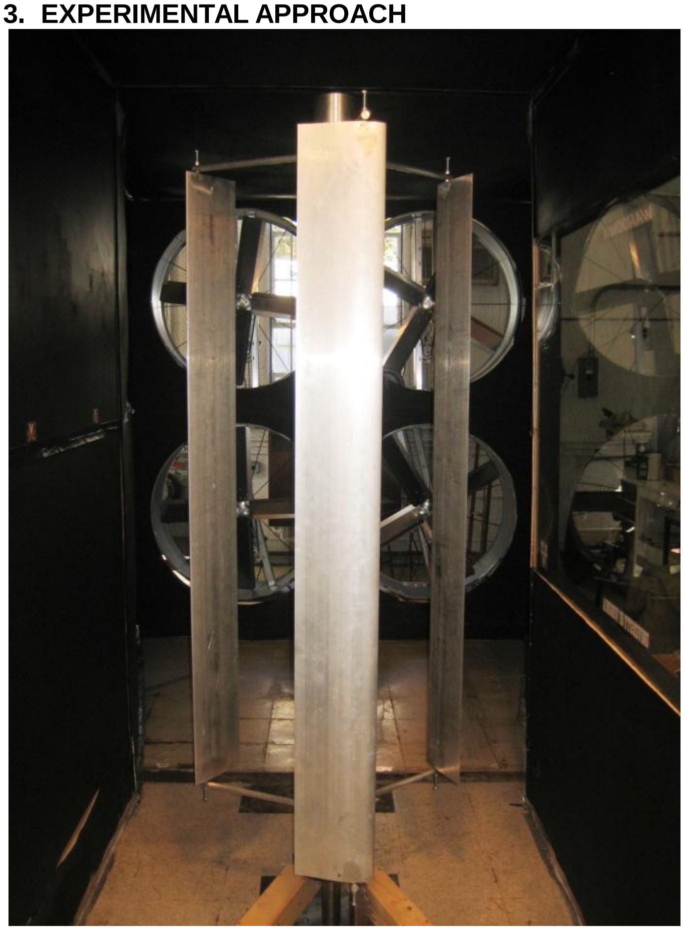

Figure 1. 2.44m VAWT experimental prototype

3.1 Turbine Description

The 2.44 m tall prototype was designed so that many of its physical properties could be altered. These properties included wing section, turbine radius, and blade pitch offset angle. A typical setup of the turbine in shown in Fig. 1. The following three sets of interchangeable airfoils were considered: a 101.6 mm chord NACA 0012 airfoil, a 120.7 mm chord NACA 8H12 airfoil, and a 203.2 mm chord NACA 8H12 airfoil. Three sets of spars of varying length were designed to screw into the rotor and allowed the rotor radius to be set to 190.5, 317.5, or 444.5 mm. Any change in diameter or blade chord in turn changed the turbine's solidity. The pitch offset of the blades could be varied continuously. For this experiment, pitch offsets from 0°-20° were investigated.

The turbine's stator consisted of a 2.44 m tall steel monopole. An aluminum rotor with an axial length of 2.16 m extended down from the top of the monopole. All blade sections spanned an axial length of 1.83 m, which was considered the actual turbine height in all proceeding calculations. All set-ups tested featured a three-bladed model and all pitch offsets were considered to be fixed-pitch offsets.

3.2 Turbine Loading

A disk brake was designed and fabricated for the purpose of applying a torque to the bottom of the rotor. This brake torque is representative of the power removed from the turbine by an electric generator. The disk consisted of a circular piece of acetyl resin material measuring 228.6 mm in outer diameter and 76.2 mm inner diameter that fit loosely around the bottom of the rotor. The brake could be raised and lowered with two lever arms. Various weights could be added to the opposing side of the lever arms introducing a range of torques to the bottom of the turbine. The lever arms and disk brake positioned at the bottom of the turbine is illustrated in Fig. 2.

The maximum theoretical power available from the incoming wind is given by [5, 6]:

$$P_{\max} = \frac{1}{2}\rho_a A_f V_\infty^3 \quad (1)$$

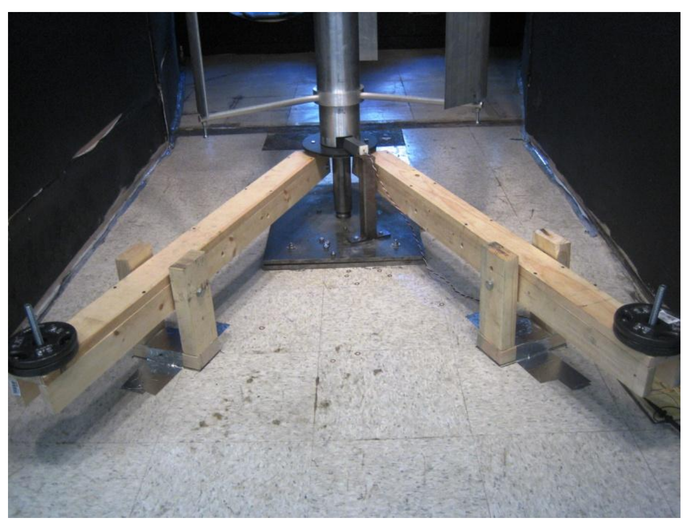

Figure 2. Friction brake and optical sensor

A friction brake was used to apply torques and simulate an electric generator. The applied friction torque was given by [7]:

$$T = \frac{\mu N}{3}\frac{D^3 - d^3}{D^2 - d^2} \tag{2}$$

The output power was then given by:

$$P_{out} = T\Omega \tag{3}$$

The kinetic coefficient of friction was determined experimentally by sliding a block of acetyl resin material down a 6061 aluminum ramp. The angle of the ramp to the floor was measured as soon as the block began to slide. This test was repeated with different weights to check for consistency. The coefficient of friction was determined to be 0.155.

3.3 Rotational Measurements

The most important measurement in this experiment was rotational speed. To measure this speed, an optical sensor was positioned at the bottom of the rotor. The sensor was mounted to a bracket so that the face of the sensor nearly touched the rotor. The mount and sensor position can be seen in Fig. 2. A black felt tape strip was placed around the bottom of the aluminum rotor, giving one measurement per revolution. An op-amp wired as a comparator was used to filter the signal producing square waves at every strip of tape. The square-wave signal was sent to a microprocessor, which recorded the revolution counter and the time occurrence. Post processing of the data was preformed with a commercial spreadsheet package where the data was graphed to show the transient speed of the turbine.

3.4 Wind Tunnel Description

The turbine was tested in an indoor wind tunnel facility. Four Ventamatic Ltd. Maxx Air 1.07 m belt drive fans were positioned in a square pattern, as shown in Fig. 1, at one end of the tunnel and directed towards the turbine. These fans were capable of producing 6.28 m^3/s airflow each. The tunnel consisted of a 2.13 m long test section with a 2.74 m by 1.52 m cross section. Front and side schematic views of the tunnel are illustrated in Fig. 3, including the position of the turbine and base plates within the tunnel. Wind speed data was collected with a hand held anemometer at a number of points inside the wind tunnel obtained at positions along the length and width of the tunnel at heights of 0.91, 1.83, and 2.44 m. These measurements averaged 3.56 m/s. This value was used as the incoming wind velocity in all power calculations.

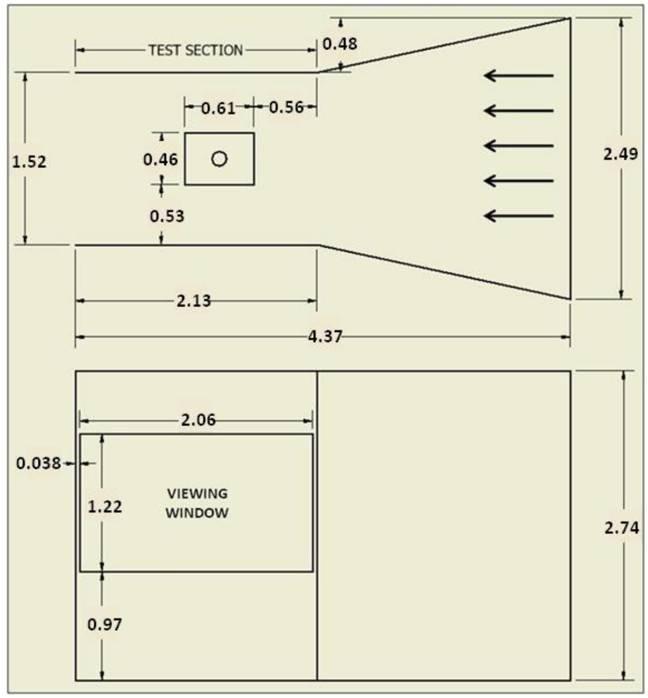

Figure 3. Wind tunnel schematic (meters)

The tunnel enclosed the test section on four sides, inevitably creating boundary layer effects on all sides of the turbine. These effects, along with turbulent flow, are sometimes eliminated or minimized in wind tunnel research. However, wind inherently contains turbulence and the ground, trees, and hillsides create boundary layer effects. The purpose of this study was not to test a turbine in ideal flow fields but to test the turbine in flows with real world disturbances. Blockage ratios and their influence on this experiment are further considered in the discussion.

3.5 Test Procedure

The goal of the experiment was to optimize the turbine's physical set-up within the given parameters to produce maximum power. The initial test matrix for each blade section considered is presented in Table 2. This matrix was completed for each of the airfoil sections described in Section 3.1. It was originally unknown where in these matrices the optimum set-up would lay; therefore, the experimental approach taken started as a broad sweep of variables with general measurements. First, the free-spinning, transient rotational speed was measured for each set-up, and the maximum rotational speed was noted. These measurements would be used to give a general idea of which set-up or set-ups might optimize power output. Any areas of the matrix with much higher rotational speeds than the others would be further investigated. For instance, if the original pitch offset "mesh" of 5 degree increments was determined to be too course, the experiment would be expanded around any local area on interest to include more offset angles.

Table 2. Example blade section initial test matrix

Pitch Offset, degrees	Rotor Radius, mm		
	190.5	317.5	444.5
0	x	x	x
5	x	x	x
10	x	x	x
15	x	x	x
20	x	x	x

The results of these preliminary tests, which are discussed in great detail below, showed that the 203.2 mm chord NACA8H12 blade set with pitch offsets of 10 and 15 degrees and rotor radii of 317.5 and 444.5 mm performed much better than any other physical set-up. These runs reached steady-state rotational speeds well above any other set-up. A refined optimization matrix, presented in Table 3, was created to explore more offset angles within this newly defined area of interest.

Table 3. 203.2 mm chord NACA8H12 revised matrix

Pitch Offset, degrees	Rotor Radius	
	317.5	444.5
10	x	x
12	x	x
14	x	x
16	x	x

The disk brake was then used to apply torque representing that which might be taken out by an electric generator. The amount of torque applied was experimentally calibrated to allow the turbine to continue to rotate as quickly as possible without slowing the turbine to a stop. The turbine was allowed to stabilize at constant rotational speed after each torque was applied and its power was calculated using Eq. (3). The applied brake torque was increased twice, providing three distinct power points for a given set-up. The torque levels applied remained constant for a given rotor radius for all pitch offset angles allowing for direct comparison of the angles. Dimensionless power coefficients were then calculated to compare the 444.5 mm and 317.5 mm radius turbines.

The average Reynolds number was calculated for each run. This non-dimensional parameter makes comparisons between different set-ups fair and can help determine the scalability of a wind turbine prototype. A single blade of a VAWT experiences a continuously changing Reynolds number as it completes a revolution due to the change in relative velocity at each point. The time-averaged tangential velocity was used in the following calculations and is defined as the rotational speed times the rotor radius. The blade chord length was taken to be an approximation of the characteristic length. The average Reynolds number for a full revolution is then calculated as:

$$\mathrm{Re}_{AVG} = \frac{\rho_a R_t \Omega c}{\mu_a} \tag{4}$$

It is important to note that the Reynolds numbers presented in this paper are calculated using only the rotor's radius. They may be used for scaling purposes in regards to the radial dimensions of a turbine, but are unrelated to the turbine's height.

General trends and observations were noted throughout the entirety of all wind tunnel testing. Section Four presents the results of these studies.

4. RESULTS

Preliminary testing of the NACA 0012 airfoil with 101.6 mm chord length indicated that these blades would not be effective in the prototype. These blades were tested at each rotor radius of 190.5, 317.5, and 444.5 mm producing respective solidities of 0.8, 0.48, and 0.34. Maximum TSRs for these blades were approximately 0.25, regardless of pitch angle or turbine diameter. In some of these cases, the turbine would return to rest even with an imparted initial rotational speed. Table 4 illustrates the TSRs reached for all runs with this wing section. These TSRs represent the maximum speeds reached by the free-spinning rotor, meaning that no braking torque was applied. Given such small TSRs under a no load condition, it was determined that this airfoil section could not produce any meaningful power within the given parameters of the experiment. Table 5 presents the average Reynolds number for all 101.6 mm chord length NACA 0012 runs. Comparing Tables 4 and 5, a strong correlation exists between rotational speed and Reynolds number with higher speeds producing higher Reynolds numbers.

Table 4. TSRs for 101.6 mm chord NACA 0012

Pitch Offset, degrees	Rotor Radius, mm		
	190.5	317.5	444.5
0	0	0.09	0.20
5	0	0.18	0.25
10	0.04	0.21	0.24
15	0.11	0.18	0.14
20	0.15	0.15	0.09

Testing proceeded with the NACA 8H12 203.2 mm chord length airfoil with the 190.5 mm rotor radius. This set-up produced a turbine solidity of 1.6. The turbine was unable to maintain any speed with this set-up at any of the pitch offset angles. The turbine simply would not work given the proportions of the blade chord, rotor radius, and the radius of the rotor's center hub without including spar length. The solidity for this turbine was very high, and perhaps too high to function given the rotor's hub radius. It appeared as if no effective wind would reach the blade as it circled the leeward side of the turbine in the wake of the rotor's hub. No data are presented for this set-up as the TSRs were all nearly zero. This configuration was deemed completely useless within the limits of this experiment and testing of this airfoil continued with the larger rotor radii.

Table 5. Reynolds numbers for NACA 0012 runs

Pitch Offset, degrees	Rotor Radius, mm		
	190.5	317.5	444.5
0	0	2177	4897
5	0	4378	6194
10	1084	5142	6064
15	2696	4447	3437
20	3683	3613	2335

These same blades were tested with rotor radii of 317.5 and 444.5 mm producing respective solidities of 0.96 and 0.69. It was clear from the free-spinning test results that these blades performed best with pitch offset angles between 10°-15°. For set-ups at both radii and pitch offset angles of 0 and 5°, the turbine reached relative slow free-spinning rotational speeds that were insufficient for power production. When the turbines were given pitch offsets of 10 and 15°, the turbine reached steady-state speeds well above any other set-ups previously tested. When the pitch offset angle was further increased to 20°, performance greatly diminished and again produced no meaningful power. The experimental approach was slightly altered, as described in the previous section, to look at more angles around these areas of interest. The turbine with the NACA 8H12 203.2mm chord length blades and rotor radii of 317.5 and 444.5 mm were then tested at 10, 12, 14, and 16 degree pitch offsets. No results are formally presented on the 0, 5, and 20° runs of these turbines; however, the turbine's poor performance during these runs is later referenced in the discussion.

Furthermore, preliminary testing of these blades within this region of set-ups revealed that the blade attachment mechanism could not withstand TSRs in excess of 2.25 due to aerodynamic forces and blade vibrations. As a result, the brake mechanism was used to limit rotational speed. This braking device would also allow for power coefficient estimations, which are much more meaningful than free-spinning maximum TSRs.

The turbine's set-up returned to the 203.2 mm chord length NACA 8H12 blades with a 317.5 mm radius and a pitch offset of 10°. As previously documented, three distinct braking torques were applied to the rotor. Table 6 shows the weights applied to the levers, force transmitted to the brake, and torque applied to the rotor as calculated with the uniform-pressure theory, Eq. (2). The turbine was allowed to accelerate to an approximate speed of 190 RPM before the first braking torque was applied. The turbine's rotational speed was allowed to stabilize before the second braking torque was applied. This process was, in turn, repeated for the third breaking torque. The 10° set-up was repeated 10 times to estimate repeatability. The average and standard deviation of the RPM over each torque application was calculated after the turbine rotational speed had stabilized. With one run removed as a statistical outlier, the 9 individual averages over a given brake torque range were taken as the data points. The student-*t* test was then used to calculate 95 percent confidence intervals in the speed measurement. Fig. 4 illustrates the average of the nine runs with error bars. The three distinct plateaus clearly represent the turbine's new steady-state speeds after each torque is applied.

Table 6. Torques applied to rotor, 317.5 mm radius runs

Weight, N	Force Applied, N	Torque (N*m)
57.9	19.4	0.18
66.7	23.4	0.21
75.6	27.4	0.25

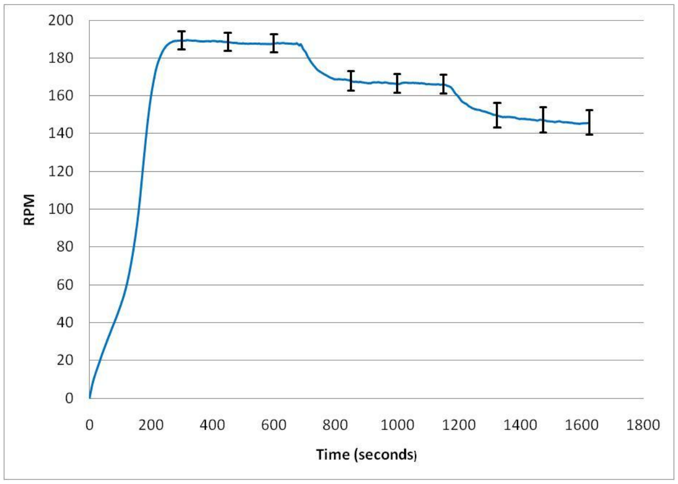

Figure 4. NACA 8H12, 203.2 mm chord, 317.5 mm radius, 10° offset, run averages with brake torque including 95% confidence interval error bars.

This analysis provides some insight into the error associated with the disk brake. It is important to note that the error bars in Fig. 4 are smaller than the drop in rotational speed experienced at each subsequent braking torque. Again, this analysis was meant to provide a very general idea of the error in the disk brake. No detailed analysis was performed on the transient ramp up period although, by visual inspection of the data, the accelerations to a steady state speed were consistent. The experiment then proceeded with two runs per offset angle to assure a certain level of consistency and to eliminate any anomalies that may have presented themselves.

The angle of attack was now varied from 10-16° by 2° increments. The average performance of each blade offset angle is shown in Fig. 5. The 12 and 14° offset set-ups behaved similarly and performed better than the 10° set-up. The 16° degree set-up produced similar speeds under the first two loads; however, it was unable to sustain the largest load.

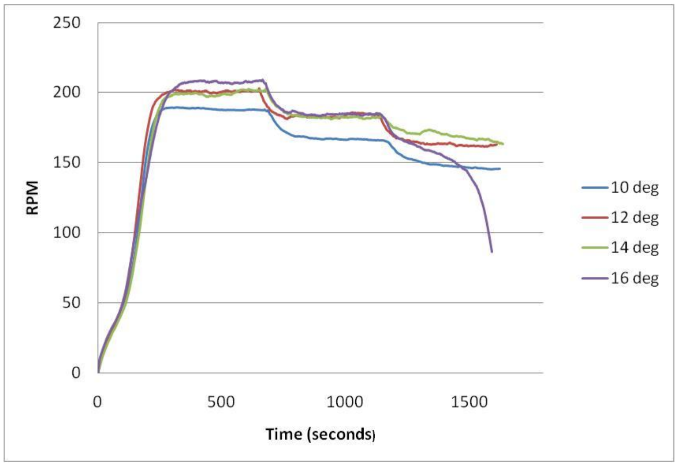

Figure 5. NACA 8H12, 203.2 mm chord, 317.5 mm radius, run averages

After the average speed was found for a given set-up, it was multiplied by the estimated braking torque to determine the power extracted by the disk brake. The power coefficient was also calculated by dividing the estimated power produced by the maximum theoretical power that this turbine could produce. The average TSRs and power calculations can be found in Table 7. Table 8 presents the Reynolds number calculations for these runs. As with the NACA 0012 blades previously tested, higher rotational speeds produced higher Reynolds numbers. Fig. 6 graphs power coefficient versus pitch offset angle for all of the load cases. A clear increase in performance is seen as the angle is increased from 10°. This performance remains constant through 12 and 14°; however, it begins to diminish at 16° as this set-up is unable to maintain any speed at the greatest load.

Table 8. Reynolds numbers for 317.5mm NACA 8H12

Pitch Offset, degrees	Applied Load, N*m 0.175	0.211	0.247
10	87250	77390	67970
12	93030	85060	75240
14	92290	84410	77740
16	96220	85510	0

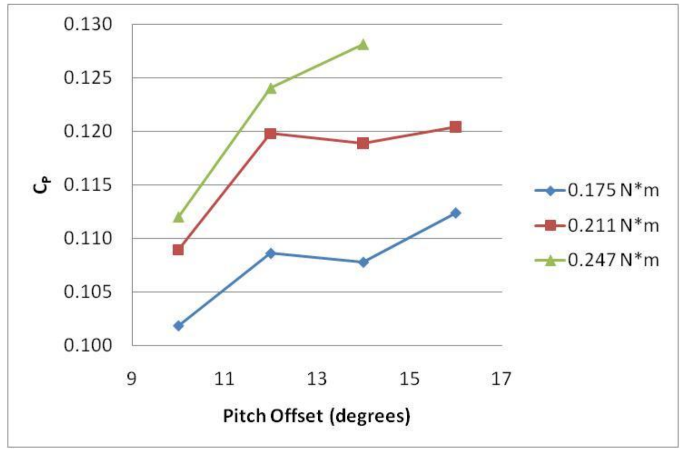

Figure 6. Power coefficient vs. pitch offset for NACA 8H12, 203.2 mm chord, 317.5 mm radius with brake torques applied.

Having explored the area of interest with the 317.5 mm radius turbine, the turbine was set up with the 203.22 mm chord length NACA 8H12 blades and a rotor radius of 444.5 mm. With an offset angle of 10°, the turbine quickly reached the same rotational speeds as the previous configuration. However, since the turbine's radius was larger, the blades reached much higher TSRs and required more braking torque. Weight applied to the levers, force transmitted to the brake, and torque applied to the rotor is presented in Table 9. Again, two runs were done for each set-up to assure consistency. Offsets of 10 and 12° produced steady-state operating conditions at each load level. The 12° offset clearly produced higher speeds at each level and thus higher power outputs.

Table 7. 203.2 mm chord NACA 8H12 Power calculations, 317.5 mm radius turbine

		0.175 N*m Load			0.211 N*m Load			0.247 N*m Load		
		TSR	P , W	c_P	TSR	P , W	c_P	TSR	P , W	c_P
Pitch Offset (degrees)	10	1.751	3.451	0.102	1.553	3.690	0.109	1.364	3.796	0.112
	12	1.867	3.679	0.109	1.707	4.057	0.120	1.510	4.201	0.124
	14	1.852	3.651	0.108	1.694	4.027	0.119	1.560	4.340	0.128
	16	1.931	3.807	0.112	1.716	4.079	0.120	0	0	0

With a 14° offset, the turbine accelerated much more slowly and was unable to maintain any speed for even the lowest applied torque level. The averaged results are presented in Fig. 7. A 16° offset caused the turbine to accelerate slowly to just over 30 RPM with no brake torque applied. This set-up produces no meaningful power and is not presented in any graphs or tables.

Table 9. Torque applied to rotor, 444.5 mm radius runs.

Weight, N	Force Applied, N	Torque (N*m)
124.6	49.5	0.45
133.4	53.6	0.48
142.3	57.6	0.52

Since this turbine's radius was larger than the previous set-up, it was capable of producing a higher maximum theoretical value of extracted power. Table 10 presents these results while Fig. 8 plots the power coefficient versus offset angle. Table 11 presents the Reynolds number calculations for these runs.

Preliminary investigations determined that the 203.2 mm NACA 8H12 blade on the 317.5 and 444.5 mm radius rotor with a pitch offset between 10-15 degrees performed far better than any other configuration in the optimization matrix. Further investigation of the 317.5 mm radius set-up showed that although a 16 degree offset produced greater power coefficients under the first two loads, it was not the most robust configuration as it stopped under the third load. Testing of the 444.5 mm radius set-up showed this performance drop at a smaller pitch offset angle of 14°. A pitch offset angle of 12° appears to be much more reliable and performed favorably throughout the testing. Increasing the rotor radius allowed the turbine to reach much greater TSRs. These tip speed ratios are much below the theoretical maximum value of 4.5 [5] but may be indicative of useful TSRs for low wind speeds as tested here. Greater speeds translated into higher efficiencies as power coefficients were larger with this radius. It is apparent from the data collected that the 203.2 mm NACA 8H12 airfoil with turbine radius of 444.5 mm and pitch offset of 12° optimized the power output of this turbine within the given parameters of the experiment.

Table 11. Reynolds numbers for 444.5mm NACA 8H12

Pitch Offset, degrees	Applied Load, N*m 0.175	0.211	0.247
10	99860	96720	92090
12	109500	105100	100200

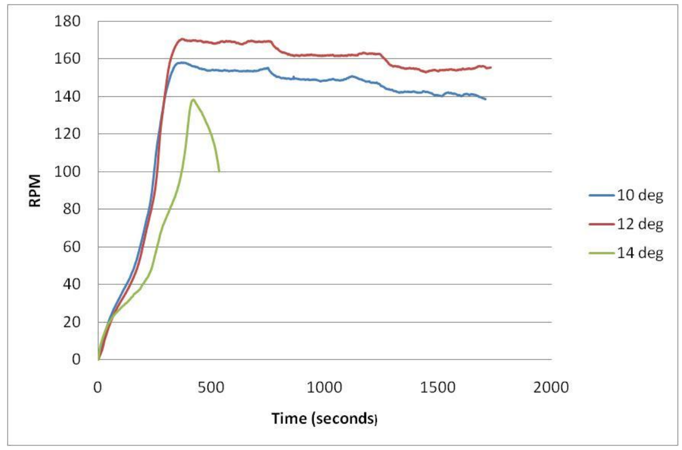

Figure 7. NACA 8H12, 203.2 mm chord, 444.5 mm radius, run averages.

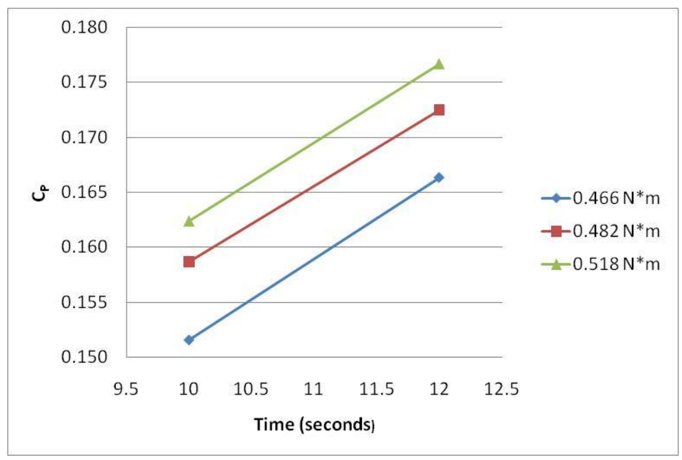

Figure 8. Power coefficient vs. pitch offset for NACA 8H12, 203.2 mm chord, 444.5 mm radius.

Table 10. Power calculations, 444.5 mm radius turbine

		0.446 N*m Load			0.482 N*m Load			0.518 N*m Load		
		TSR	P , W	c_P	TSR	P , W	c_P	TSR	P , W	c_P
Pitch Offset	10	2.004	7.190	0.152	1.941	7.526	0.159	1.848	7.703	0.162
(degrees)	12	2.198	7.889	0.166	2.110	8.181	0.173	2.010	8.378	0.177

The third set of blades, the 120.7 mm chord length NACA 8H12, were tested very briefly. The results of the similarly sized NACA 0012 blades seemed to suggest that the chord length of the blades was simply too small to drive the turbine. The turbine was initially set up with this set of blades and a 317.5 mm rotor radius. The pitch offset was set to 10°. Testing of both the previous blades suggested that this would be one of the most optimal settings. After running for over 30 minutes, the turbine had accelerated to 20 rpm. The pitch offset was set to 14 degrees, and again, the turbine accelerated to around 20 rpm. These poor results as well as the results from the NACA 0012 blade led to the conclusion that these blades could never reach the speeds seen with the 203.2 mm chord length NACA 8H12 airfoil. They would therefore never be able to optimize this wind turbine within the experiments parameters. Based on this observation, no further testing was performed. Having successfully completed the optimization matrix and finding an optimized set-up the testing was concluded.

5. DISCUSSION

This experiment serves as a documented approach for small scale testing prior to implementation in the field. A scaled model of a potential large scale prototype was built with varying physical parameters for the purposes of optimization. A systematic approach was taken in which these parameters were incrementally changed on a broad scale. After a localized group of certain configurations demonstrated superior performance, the parameter increments were decreased until an optimal design was found. In addition to providing invaluable insight into the dynamic response of this particular turbine, the data obtained can also be compared with CFD analysis for validation purposes. General trends were observed that could potentially be used for design guidelines and criteria. These trends and observations are discussed below.

As described earlier, blockage ratios in closed wind tunnel tests can impact the results of an experiment and care must be taken not to misinterpret the results when they are present. Blockage ratio is defined as the largest cross-sectional area of an object normal to the incoming flow over the wind tunnel's cross-sectional area. High blockage ratios can limit a flows expansion, thus increasing its velocity around an object. Previous literature suggests that ratios below 6-7.5% have minimal impact on the flow [3]. The exact blockage ratio of a VAWT is hard to calculate as its cross-sectional area is constantly changing. The solid cross-sectional area of a turbine at any given instance in time is very small; however, its swept area is much larger. Using the turbine's frontal area provides a very conservative estimate for the blockage ratio but is commonly reported in VAWT testing.

Using this estimate, the blockage ratios for the 190.5, 317.5, and 444.5 mm radii turbines tested in this experiment are calculated respectively as 16.67, 27.78, and 38.89%. The value of the smallest radius turbine is similar to those blockage ratios of 14 and 16.7% presented in similar studies which viewed these values as having negligible effects [3]. Although the apparent frontal area (and thus the blockage ratio) of a VAWT is questionable, it is assumed that each increase in radius in this experiment contributed positively to the turbine's performance. Although the magnitude of the blockage ratio's contribution is unknown, and may even be insignificant, its impact is considered in the remainder of the discussion.

This experiment tested two completely different airfoil sections; the NACA 0012 symmetrical airfoil, and the NACA 8H12 cambered airfoil. It is very important to note that the results obtained from each airfoil are unique to that airfoil. No attempt is made at making direct comparisons between the performances of the two distinct airfoils; however, some trends are presented that are evident in tests involving both. One of these trends is the lack of performance by both the 101.6 mm chord length NACA 0012 blades and the 120.7 mm chord length NACA 8H12 blades. These airfoils at these specific chord lengths were unable to produce any meaningful power regardless of rotor radius or pitch offset angle. The forces experienced by these two sets of blades were simply not great enough to turn a turbine of this size with any meaningful speed.

The non-dimensional parameter of vertical aspect ratio (AR) is defined as the height of the turbine's blades over their chord length. The two sets of blades described above produced aspect ratios of 18 and 15.16, respectively. These values are relatively high when compared to the experimental turbines described in the literature, which all had ARs in the range of 4-8.3. The NACA 8H12 blades with a 203.2 mm chord length used in this experiment produced an AR of 9, much nearer to those seen in the literature, and performed very well. These findings suggest extremely high ARs have a negative impact on turbine performance. Although performance with the 203.2 mm chord length was still heavily dependent on the pitch offset, the importance of creating a low AR during initial turbine design was demonstrated in this experiment. Of course, varying the AR of a turbine presents another opportunity for optimization, which was not explored in this study. It is also highly possible that had a NACA 0012 airfoil with 203.2 mm chord length been available for testing, it would have performed similarly to the NACA 8H12 of the same size.

Most of the VAWT literature looks at the solidity of a turbine as a non-dimensional value that can be used to compare the performance of turbines of different sizes. Some literature suggests that higher solidity turbines reach lower TSRs and are therefore less efficient [3]. The 120.7 mm chord length NACA 8H12 blades were tested with a rotor radius of 317.5 mm and thus a solidity of 0.57. These blades were unable to produce any useful power. When the larger 203.2 mm chord length NACA 8H12 blades were tested with the same rotor radius and a solidity of and 0.97, they were able to produce significant power. As both set-ups had the same rotor radius, it is assumed that any swept area blockage effects had the same effect on both set-ups. In this case, the higher solidity turbine performed much better than the lower solidity turbine with the same rotor radius, pitch offset, and airfoil shape. This observation strengthens the claim that a certain AR is necessary for acceptable turbine performance. Perhaps solidity can be used to describe trends in turbine performance, but only when keeping other turbine properties, such as AR, in mind. There is obviously some connection between AR, solidity, pitch offset angle, and turbine performance. Although this connection remains unknown, this experiment clearly shows a strong sensitivity of VAWT's performance to its physical parameters.

The turbine's sensitivity to pitch offset angle is evident in the results of the NACA 8H12 blades with 203.2 mm chord length. With a radius of 317.5 mm, the turbine could not sustain any rotational speed with a 0° pitch offset angle and barely rotated at a free-spinning speed of 10 rpm with an offset angle of 5°. At 10°, the turbine accelerated to rotational speeds up to 200 RPM. At an angle somewhere between 5° and 10°, the turbine with this particular radius began to perform at a much higher level than it would with a slightly lower offset angle. This sensitivity is also seen on the other end of the spectrum with the same set of blades with 444.5 mm turbine radius. The turbine's efficiency dropped significantly at a pitch angle of 14°, even though peak efficiency was obtained at a pitch angle of 12°. A difference of only 2° separated the best performing physical set-up found in the study to one that produces very little power.

Blades of a VAWT experience a complete cycle of angles of attack, just as do Reynolds numbers, as they make a full revolution due to a constantly changing relative velocity. However, the time averaged angle of attack during a single revolution is equal to the blade's pitch offset angle. The results of this experiment suggest that the optimal pitch offset angle for the NACA 8H12 203.2 mm chord length airfoil with both the 317.5 and 444.5 mm turbine radii is somewhere near 12°. As mentioned, performances declined very quickly if this value was only slightly decreased or increased. This angle is close to the angle at which flow separation can begin to be an issue. Flow separation is well known to cause lift coefficients to drop drastically and drag coefficients spike. Perhaps the optimal offset angle for a VAWT is near the flow separation angle for a given airfoil. By approaching the angle of flow separation, an airfoil sees its most extreme negative pressure over its leading edge which may equate to maximum power in a VAWT. The National Advisory Committee for Aeronautics (NACA) performed wind tunnel testing on the NACA 8H12 airfoil in 1946 in which they presented lift versus angle of attack curves [8]. The curves for this airfoil clearly show a peak in lift coefficient at 12°. Lift coefficients increase gradually from 0-12° and then drop rapidly at angles greater than 12°. It is unknown whether this phenomenon would definitely exist in other experimental turbines, but the results of this study, coupled with the NACA airfoil data, certainly seems to suggest that there is a correlation.

A few general trends were observed in this study in regards to self-starting. The turbine self started sporadically with the mid and large radii of 317.5 and 444.5 mm. It appeared as though the turbine's starting azimuth position in relation to the wind and its blade pitch offset had the biggest influence on self-starting. With one spar perpendicular to the incoming wind and its blade's leading edge facing into the wind, the turbine always self started during tested. Starting positions close to this position also tended to self start. Alternatively, with one spar perpendicular to the incoming wind and its blade's trailing edge facing the wind, the turbine rarely self started. These observations were strictly qualitative and no systematic experimental method was implemented to test the turbine's self starting abilities at certain positions. When the turbine did not start, a small rotational speed was imparted by hand until one of the blades leading edges started to face the wind.

The turbine was also more likely to self start with a larger blade pitch offset angle. Smaller angle set-ups using 0° and 5° were the least like to self-start. Blade offset angles around 10° performed neutrally and always accelerated quickly as long as one blade was positioned favorably as described above. Blade offset angles of 15° and 20° were the most likely to self-start, but were suboptimal in power output. It appeared as if a certain level of pitch offset was necessary for self-starting. Although inconclusive, these observations suggest that self-starting is possible with sufficient pitch offset and a certain level of wind variability or turbulence.

This study points to additional experiments that could provide even more insight into the dynamic characteristics and physical optimization of vertical axis wind turbines. The relationship between AR, solidity, and pitch offset needs further investigation. This study has provided a sound approach for the incremental and systematic change or a turbine's physical parameters. This approach can be implemented experimentally or with validated CFD software.

The robustness of these parameters should also be checked. This experiment was only able to produce one low wind tunnel speed of 3.56 m/s. A VAWT in the field would obviously encounter a variety of wind speeds. It is anticipated that each wind speed will cause the turbine to react differently. The optimization should be performed over the entire range of design wind speeds. A fixed-pitch offset machine may have to be designed with the pitch offset angle that allows for sufficient operation over the range of design wind speeds.

The results of this study mostly account for the NACA 8H12 airfoil. Each airfoil will obviously have a unique set of characteristics and will behave different when used on a VAWT. Investigation of different airfoils should be performed to determine if a certain airfoil, or family of airfoils, is more suitable for VAWTs. It was hypothesized that a blade's ideal offset may be the angle at which it experiences flow separation, although future tests are needed to validate this theory.

6. CONCLUSIONS

The results of this experiment conclude that the 203.2 mm chord length NACA 8H12 blade with a fixed pitch offset of 12° and rotor radius of 444.5 mm performed optimally over all other physical configurations tested with a wind speed of 3.56 m/s. This set-up reached a maximum power coefficient of 0.177 at a TSR of 2.0. These values can be compared to the theoretical optimum of coefficient of power at 0.40 and TSR of 4.5 [6]. The results reported in this paper for the scale model turbine are clearly well below the optimum; however, the values are in the right range for a low wind speed test in the range of nearly half of the optimum coefficient of power and TSR. Thus, the test configurations are considered to be close enough to the optimum values to indicate that the optimum rotor configuration test results would be valid at higher wind speeds for this VAWT turbine.

This study suggests a strong correlation between the optimal pitch offset angle of a given airfoil and that airfoil's flow separation angle. The importance of finding a proper pitch offset angle and AR is demonstrated in the results. It has shown that perhaps solidity should be looked at as a compliment to these other properties. Although the correlation between these parameters is currently not completely understood, it certainly exists and needs to be heeded in the design and testing phases of turbine prototypes.

This study has proven the effectiveness of small scale testing and optimization. Simple wind tunnel tests such as this can save time and money while optimizing performance coefficients. As data from these tests increase, certain trends will become apparent eventually leading to a uniform set of design guidelines and criteria. Vertical axis wind turbines will then provide a means of harnessing the generally untapped energy contained in low speed winds.

Most of the results presented in the study hold true regardless of blockage ratio. Blockage effects may have increased the performance of the largest radius turbine. The extent of these effects is unknown and may even by negligible. Future tests are needed to determine the affect of blockage ratios on VAWTs and correction factors.

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