Experimental Set-Up Design and Testing of Vertical and Horizontal Axis Wind Turbine Models in a Subsonic Wind Tunnel

Mosfequr Rahman[1], Travis Salyers[2], and Emile Maroha[3]
Associate Professor[1], Graduate Student[2] and Graduate Student[3]
Mechanical Engineering Department
Georgia Southern University
Statesboro, Georgia 30460

Abstract

Wind alone can fulfill most of the energy requirement of the world by its efficient conversion into the usable form of energy. Wind turbine converts the wind energy into mechanical energy and that mechanical energy is used for the production of electricity. There are two types of primary wind turbine; they are horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT), both of which boast of being better than the other. HAWTs include both upwind and downwind configuration with various performance enhancers such as diffusers and concentrators. HAWT is more popular because they have better efficiency, but only suitable for places with high wind speed. On the other hand, VAWT can run at low wind speed, independent of wind direction and can be installed anywhere with cheapest cost.

A renovation has recently been completed in the energy science research laboratories at Georgia Southern University to adapt to growing interest in wind energy technology teaching and learning. The existing subsonic wind tunnel was modified and upgraded to test both vertical and horizontal axis wind turbine models. An extension to the wind tunnel was designed and fabricated by the wind energy research group. In the extended portion, new fixtures are utilized to allow for quick removal and installation of different turbine models for testing. The new extension includes clear acrylic sheet tunnel walls for complete visualization of models inside the tunnel during experiments. Various vertical and horizontal axis wind turbine models have been designed and constructed for testing. SolidWorks is used for designing CAD models of turbine blades, and the various models are 3D printed for experimentation. ANSYS Fluent software is used to study the dynamic flow around the blades. Present experimental results are compared with other experimental and numerical results for learning. The subsonic wind tunnel and turbine models designed and constructed during this work provide a powerful tool for engineering teaching and research.

Keywords

Wind Tunnel, VAWT, HAWT, CFD.

Introduction

With the global energy demand rising to unprecedented numbers, the need for alternative energy sources is ever prevalent. Wind energy is one of the most popular renewable sources today due to its year-round availability and pollution-free nature. Because of this, many works have been completed regarding wind energy conversion systems. The two primary types of conversion systems are horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). HAWTs have been in practice for decades and are heavily favored over VAWTs for large-scale power generation; however, research of VAWTs has gained growing interest in recent years. Although VAWTs has less efficiency, but with the improvement of the design and performance of VAWT, it is possible to make it more attractive, efficient, durable and sustainable for small-scale and off-grid power generation applications.

Literature Review

Experiments help to determine the effects of different rotor geometries on the torque and power coefficients of turbines. Once a numerical investigation has provided insight on a particular turbine, an experiment should be designed to validate the results. Rui-Tao et al.[1] developed a simple wind tunnel specifically for VAWT testing. The straight-flow wind tunnel test equipment information was made available to those who wish to verify numerical simulations through experimentation.

Computational Fluid Dynamics (CFD) simulations combined with experimental studies provide the most informative results for VAWT research. CFD approach is an inexpensive method for predicting performance prior to fabricating models. Also, it can play a crucial role in identifying optimum design parameters. According to Islam et al.[2], the best numerical models validated for VAWT computations fell into three categories. The three categories were momentum model, vortex model, and cascade model. Each of these had specific advantages and disadvantages, but it was concluded that the cascade model gave smooth convergence at higher tip-speed ratios with reasonable accuracy. For drag-type rotors, Pope et al.[3] presented a new correlation for performance analysis. The correlation predicted power coefficient in terms of dimensionless numbers and specific turbine geometries. The robust correlation was extended to various rotor geometries. This CFD technique proved to be a useful design tool for improving Savonius VAWTs.

Fei-Bin Hsiao et al.[4] performed test of three different HAWT blade shapes, seen in Figure 1, using Experimental and Numerical Methods. The first shape is an optimum (OPT) blade, the second is an untapered and optimum twist (UOT) blade, and the third blade is untapered and untwisted (UUT).

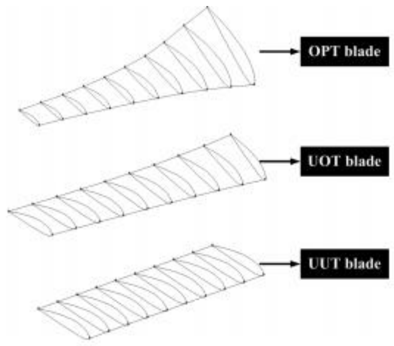


Figure 1: Three test blade models for wind tunnel experiment[4].

The first part of this method consists of predicting a blade performance curve using the improved Blade Element Momentum (BEM) method followed by the experimental method in the wind tunnel. This method consists of measuring the mechanical torque generated by the blade using the torque transducer installed on the shaft between the blade and the generator. The CFD method is then performed to analyze and verify the performance of different types of blade shapes. They concluded that the OPT blade is better than the UOT blade because its measured power coefficient is higher over a wider range of tip speed ratios. However, these blades have the same maximum power coefficient at different tip speed ratio points while the UUT blade obtains the lowest Cp value because it almost always operates in stall conditions. The ultimate goal of this research is to establish and improve the experimental wind energy facilities at the Georgia Southern University (GSU) to uplift the engineering education and teaching in the area of wind energy. Based on this goal this current research has the following objectives:

- Upgrade the previous electric motor of the existing subsonic wind tunnel
- Install variable frequency drive to control steady wind speed of the tunnel
- Design and development of the dynamic torque measurement system
- Fabricate new model testing section in the wind tunnel
- Outline procedures for CFD investigations with ANSYS Fluent

Mathematical Expressions

Reynolds Number: $\boldsymbol{Re} = \frac{\boldsymbol{VD}}{\boldsymbol{\nu}}$ (1)

Rotor Area: $\boldsymbol{A} = \boldsymbol{DH}$ (2)

Torque Coefficient: $\boldsymbol{C_q} = \frac{\boldsymbol{T}}{\frac{1}{4}\boldsymbol{\rho ADV^2}}$ (3)

Angular Velocity: $\boldsymbol{\omega} = \frac{\boldsymbol{2\pi N}}{\boldsymbol{60}}$ (4)

Tip Speed Ratio: $\boldsymbol{\lambda} = \frac{\boldsymbol{\omega D}}{\boldsymbol{2V}}$ (5)

Power Coefficient: $\boldsymbol{C_p} = \frac{\boldsymbol{P}}{\frac{1}{2}\boldsymbol{\rho AV^3}} = \frac{\boldsymbol{T\omega}}{\frac{1}{2}\boldsymbol{\rho AV^3}} = \lambda \boldsymbol{Cq}$ (6)

Wind Tunnel Modifications

This research work consists of two fundamental parts. The first part involves modification and improvement of the existing wind tunnel. The second portion focuses on the design, fabrication, and development of a dynamic torque measuring test set-up for various VAWT and HAWT models. The following are the features of the existing wind tunnel setup before modification at the university.

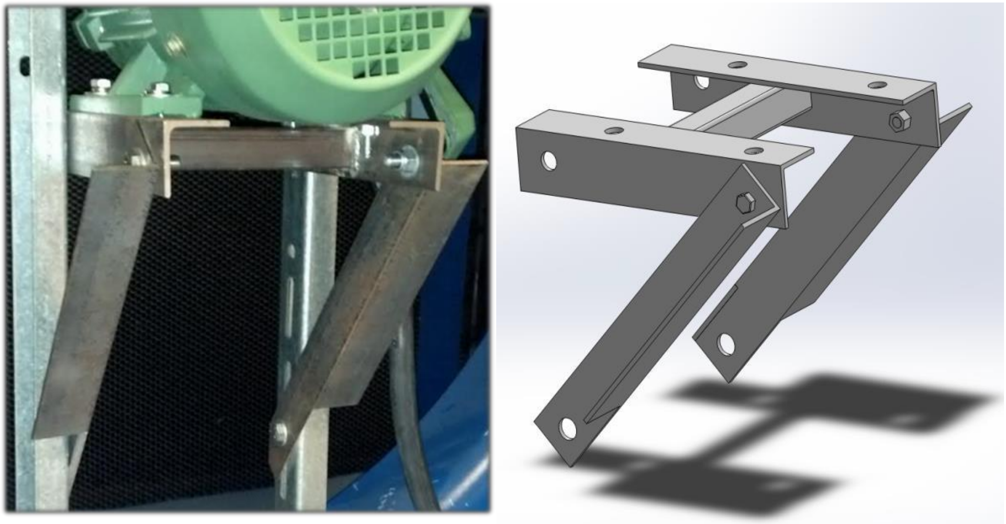
- It utilized a Fasco ½ horsepower two-phase electric motor driving a 3 foot diameter fan inside of a 13 foot long subsonic wind tunnel.

- The fan, powered by the two-phase motor, only produced wind speeds of approximately 10 miles per hour and did not possess the capability to be adjusted to various wind speeds easily and accurately.

An essential part of this educational research was to upgrade the wind tunnel and allow for much more accurate and practicable experiments. The following are the features of the current wind tunnel.

- It has a 1 horsepower, 3-phase electric motor as shown in Figure 2(a).

- Three- phase electric power is a common method of alternating-current electric power generation, transmission, and distribution.



(a) (b)

Figure 2: (a) Final bracket assembly, (b) SolidWorks rendering of mounting bracket.

The implementation of this type of motor enables the user to precisely alter a frequency being transmitted to the junction box of the motor and vary the wind speed in exceedingly small increments if desired. Since the previous motor weighed 13 pounds less than the new motor, and discrepancies between mounting locations on both motors existed, a custom-made high-strength bracket as shown in Figure 2(b) was required to accommodate for the improved system. 1 ½ inch angle mild steel was chosen to create the new bracket because of its slim profile and high compressive strength.

The existing mounting location inside the wind tunnel was kept as two vertical steel bars that are centrally located and 7 inches apart when measured from the inside of one rail to the inside of the opposing. The angle steel was cut to the appropriate length to create mounting locations for the bolt holes on the bottom of the 1 HP electric motor. Notches were cut to allow for easy and flush mounting of the bracket to the vertical support rails. To provide additional and necessary support, the mounting apparatus was fitted with 45° diagonal steel braces that transmit the load created from the mass of the motor to the base of the support rails and a section of square stock was welded to join the two parts of the bracket. The motor mounting holes were located to center the motor precisely in the middle of the tunnel to allow for the concentric positioning of the fan blades inside the circular curtain of the wind tunnel. To reduce the vibration effect when an electric motor is in operation, Poly-lock nuts were used to secure the motor to the custom bracket, and the bracket to the vertical rails. The final assembly of the bracket can be viewed in Figure 3(a).

A variable frequency drive (VFD) was included in the improvements to the pre-existing wind tunnel system. The now-installed Huanyang 1.5kw, 7amp, 220 volt variable frequency drive, shown in Figure 3(b), draws power through a wall source and transmits fluctuating frequencies (measured in hertz in this application) to the upgraded electric motor. The RPMs of the motor depend entirely on the frequency transmitted from the VFD. To allow for maintainable and consistent power, the VFD was wired in the motor’s junction box in a low-voltage setup with the high-voltage wires bridged according to the indicator plate schematic. The drive was installed and programmed using the function keys and included parameter’s list to meet the specifications that are required to run the motor, which responds to frequencies approaching 60 hertz. With this unit also comes the ability to ramp power to the motor. This allows the user to alter the time that it takes for the inverter to increase the frequency from 0Hz to any given operating frequency. This capability permits smoother, more stable acceleration of the output shaft.

(a) (b)

Figure 3: (a) Installation of Iron Horse electric motor, (b) Huanyang variable frequency drive.

In order to measure torque while turbine models were rotating, a dynamic torque sensor with data acquisition was needed. An Omega benchtop display, seen in Figure 4 was installed to display torque data. The display was connected to a rotary torque transducer. The dynamic torque measurement subsystem and schematic can be seen in Figure 5.

Figure 4: Omega digital panel meter.

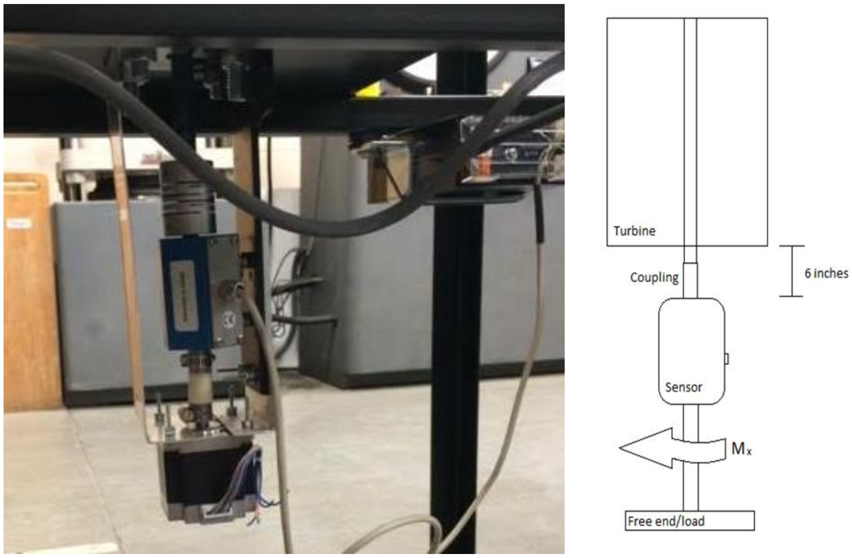


Figure 5: Dynamic torque measuring.

New Model Testing Section

In the previous state of the wind tunnel, a frame was placed at the airflow outlet containing models for testing and a reaction torque transducer. The sensor and model testing frame, shown in Figure 6, measured torque for a limited amount of load and also was not that accurate. Because that set-up could not do proper alignment of the shaft, sensor and load. Not only that, wind that was coming from the wind tunnel was not adequate to make the turbine models rotate uniformly and with faster speed to produce good amount of torque. That lagging of the previous test set-up gave the researcher the motivation to set-up a new test section inside the wind tunnel.

Figure 6: Previous state of wind tunnel experiment.

The researchers at Georgia Southern University wanted to measure the torque produced by the VAWT model while the turbine blades are rotating due to the wind flow around the blades. To achieve this goal, a new test section was designed and built by faculty and students of wind energy research group. The model test section was enclosed with acrylic doors so that researchers have full access to change models and visibility of the models during experiments. A SolidWorks model of the frame, built with angle steel and square tubing can be seen in Figure 7. The new frame was located after the fan and a honeycomb section to provide for laminar flow through the new testing section.

Figure 7: CAD model of new section of the wind tunnel.

The entire frame was built by graduate students in the machine shop on campus. The first step was cutting purchased material to design specifications with a horizontal band saw, shown in Figure 8. Also, a CNC plasma cutter was used for cutting four steel plates to which casters were fastened at the bottom of the structure.

Figure 8: Cutting material with horizontal band saw.

Angle steel was then welded to create the outside flanges which connect the frame with the existing wind tunnel. The inlet and outlet of the testing section measure 40” × 40”. Square steel tubing was used to add strength to the base as well as the bottom of the tunnel. A 12” × 12” steel plate was welded in place in the center of the testing section to provide support for various fixtures for all types of experiments. Construction of the frame and the completed test section on casters are shown in Figures 9 and 10.

Figure 9: Construction of angle steel frame.

Figure 10: Completed test section frame.

After completion, the frame was moved to the renewable energy research laboratory. Displayed in Figure 11, the new tunnel section was connected with the existing wind tunnel. The new positioning of models inside the wind tunnel and directly behind a honeycomb section provides more consistent, laminar airflow for experiments.

Figure 11: New test section installed with existing wind tunnel.

One of the professors of the mechanical engineering department of Georgia Southern University, who is also the first author of this paper, has developed a new course on Wind Energy for both undergraduate and graduate students. That course will be offered in the coming up semesters in the mechanical engineering department. A portion of that course content will have a case study, testing and experimentation of various wind turbine models using wind tunnel. This newly developed wind tunnel and test set-up will be used in that course for teaching and learning purpose. Then, it will be a unique teaching feature for Georgia Southern University as compared to any other universities within the 200 miles diameter in the state of Georgia.

Experimental Procedure

Before testing, a wind speed profile should be developed in order to determine average wind speed flowing over the models. Wind speed measurements are made vertically along the wind tunnel testing section using an anemometer. The measurements are plotted and compared to the wind speed setting of the variable frequency drive.

For wind turbine experiments, data are collected for wind speed, RPM, and average torque. RPM is measured with a handheld laser tachometer. The torque data are collected by the torque transducer and benchtop display seen in Figure 5. Using the new variable frequency drive to control wind speed, data are collected over an appropriate range of tip-speed ratios.

Numerical Procedure

In previous studies, only 2D and static simulations have been used to measure pressure and air velocity around turbine blades. To improve the performance of the VAWT, a group of graduate and undergraduate students are working in the wind energy research laboratory of Georgia Southern University under the supervision of a professor who is also the first author of this paper. This group of students are doing various model design, 3D printing and numerical simulation on those VAWT models. From their simulation it was found that twisted bladed VAWT model gave increasing performance. An example model designed by that students groups can be seen in Figure 12.

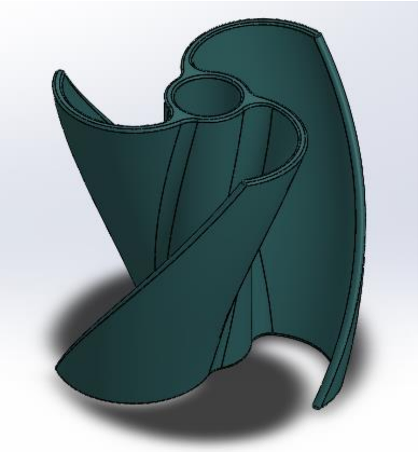


Figure 12: CAD model of VAWT with twisted blades.

Fabricating models for wind tunnel testing can be time consuming and expensive, so accurate CFD modeling was needed in order to predict which designs would be more energy efficient. Using 3D, transient analysis within ANSYS Fluent software, the researchers were able to conduct realistic simulations of complex blade geometries. Researchers completed solid models of new VAWT designs and imported them into ANSYS DesignModeler. A cylindrical region was then created around the blades to be a rotating zone as well as a stationary far-field enclosure. A wireframe view of the blades and fluid domains can be seen in Figure 13.

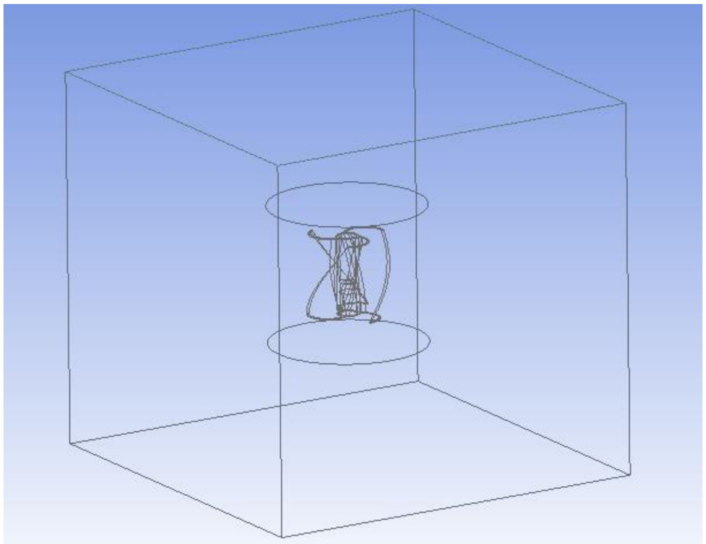


Figure 13: Fluid domain in ANSYS DesignModeler.

An interface was created between the two zones so that fluid may pass through. The fluid domains consisted of tetrahedral elements meshed with ANSYS Meshing. Experimental results were used to impose boundary conditions including air velocity inlet, rotational speed of the blades, and pressure outlet. An example is mesh is displayed in Figure 14.

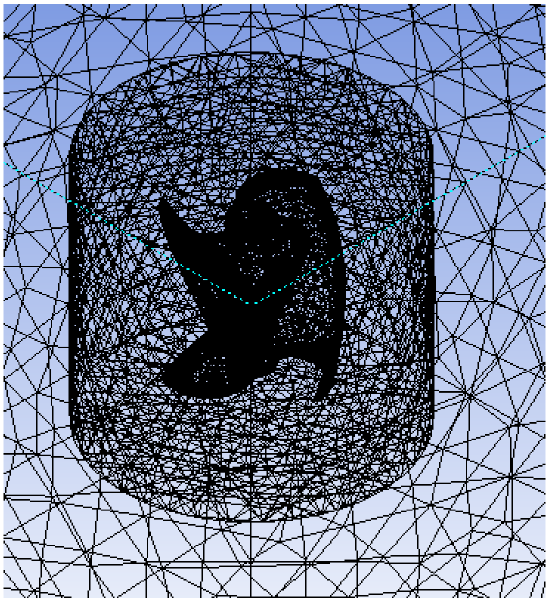


Figure 14: Tetrahedral mesh with ANSYS Meshing.

The realizable k-epsilon turbulence model was used for each solution. In each case, a static simulation with moving reference frame was used to initialize the transient sliding mesh model.

Coefficient of drag and moment were monitored over time with accurate reference values for one full rotation, as can be seen in Figure 15. From the coefficient of moment, the power coefficient of the wind turbine can be calculated using equation (6).

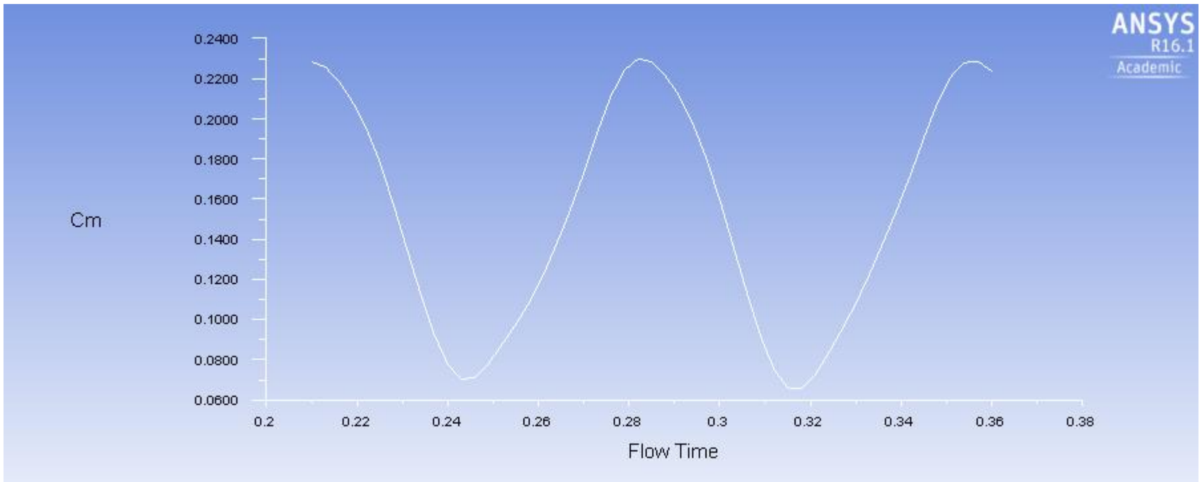


Figure 15: Transient monitor of torque coefficient.

Analysis

Once torque data are calculated, analysis must be done to compare the performance of the models to other research. Non-dimensional coefficients are used for comparison to other similar research and validation of the experiment. Three of these universally used non-dimensional entities are considered for this study. The power coefficient describes the energy conversion efficiency of the turbine. Torque coefficient is a non-dimensional representation of rotor torque, which is proportional to power produced. Tip-speed ratio is defined as the ratio of the blade tip speed to the free-stream wind velocity.[5]

Results and Discussion

After numerical and experimental values are collected, the following sample calculations are performed for each data set. These calculations provide non-dimensional values relating to the performance of the models which can then be used to compare with the other research. For each experimental investigation, a single Reynolds number must be determined for the specific testing conditions in order to describe flow conditions. The Reynolds number is calculated using equation (1), where $\boldsymbol{V}$ is wind velocity in $\boldsymbol{m/s}$, $\boldsymbol{D}$ is overall rotor diameter in $\boldsymbol{m}$, and $\boldsymbol{\nu}$ is kinematic viscosity of the fluid in $\boldsymbol{\frac{m^2}{s}}$.

An important value for comparison of VAWT performance is the torque coefficient. In order to find the coefficient for each turbine, the rotor area must first be calculated using equation (2), where $\boldsymbol{H}$ is rotor height in $\boldsymbol{m}$. From the experimental torque data, the torque coefficient can be determined. This non-dimensional number is calculated using equation (3), where $\boldsymbol{T}$ is torque in $\boldsymbol{N \cdot m}$, $\boldsymbol{\rho}$ is air density in $\boldsymbol{\frac{kg}{m^3}}$, and $\boldsymbol{A}$ is rotor area in $\boldsymbol{m^2}$. Another useful non-dimensional term for comparing efficiency of VAWTs is the power coefficient. First the angular velocity of the rotor must be calculated by equation (4), where $\boldsymbol{N}$ is the measured revolutions per minute. Once the angular velocity is determined, the tip-speed ratio of the rotor is solved using equation (5).

The power coefficient for the system is then solved. As can be seen by equation (6), the power coefficient is found from the product of tip-speed ratio and coefficient of torque. Power coefficient ($\boldsymbol{C_p}$) and tip speed ratio ($\boldsymbol{\lambda}$) should be plotted for each turbine that is tested. A sample plot of $\boldsymbol{C_p}$ versus λ for various types of wind turbines can be seen in Figure 16.

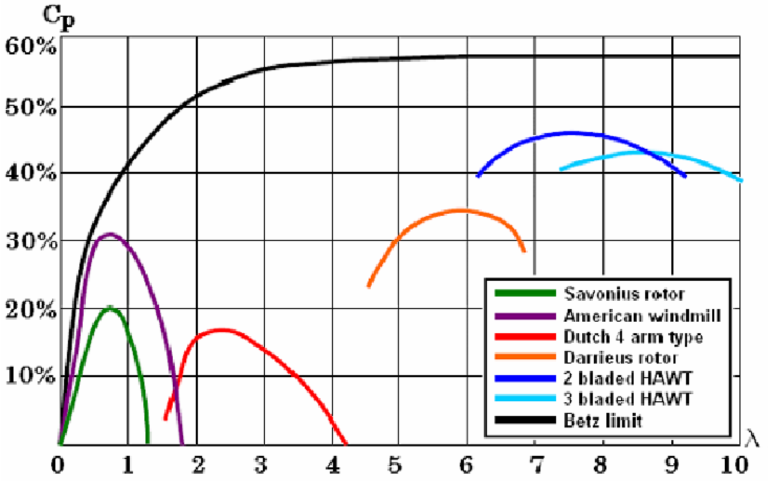
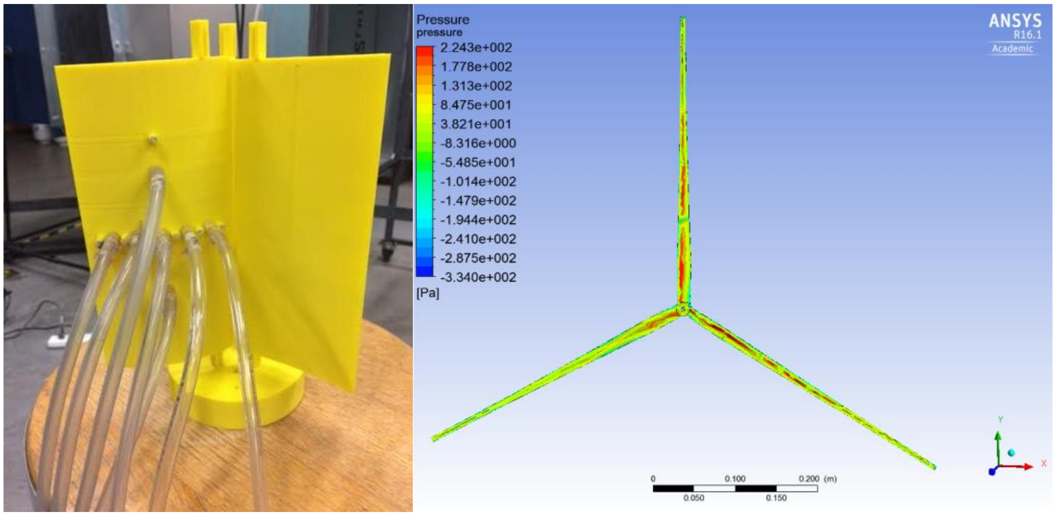


Figure 16: Power coefficient versus tip-speed ratio for popular wind turbine designs[6].

This plot is the focal point of the intended research, and much discussion can be made from this result. The occurrence of maximum power coefficient and its corresponding tip-speed ratio can easily be identified and compared to the efficiency results of other studies involving VAWT and HAWT designs.



(a) (b)

Figure 17: (a) 3D printed VAWT model with pressure transducers and (b) pressure distribution on HAWT CAD model in ANSYS Fluent.

With the completion of the experimental set-up, Georgia Southern students have begun designing their own prototypes for testing. Figure 17(a) shows a 3D printed VAWT model with the blade pressure measuring system for future experiment. Figure 17 (b) shows pressure distribution on a HAWT CAD model in ANSYS FLUENT for future numerical simulation studies.

Future Plans

Future objectives for the GSU subsonic wind tunnel include:

- Install smoke wire to visualize flow over different wind turbine models and airfoil blades
- Add additional honeycomb section in front of testing section for more laminar flow around models
- 3D printed models and fixtures for various experiments

Conclusion

The recent upgrades to Georgia Southern University’s energy science laboratory provide a successful teaching tool for computational fluid dynamics and wind energy research. The wind tunnel and turbine models designed and constructed during this work was accomplished by undergraduate and graduate students under the direct supervision of the faculty member. Objectives completed for this research include design and fabrication of a new test section with clear acrylic doors to enclose models and provide more laminar flow. A dynamic torque measurements system was installed to collect torque data for turbines during rotation. A more powerful motor with variable frequency drive was successfully mounted to better control wind speed inside the tunnel up to 13 m/s. In addition to experimental set-up, methodology for developing 3D, transient fluid flow simulations using ANSYS Fluent is provided. Computational fluid dynamics is an important step for understanding experimental results and redesigning prototypes for optimal performance.

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Mosfequr Rahman

Dr. Mosfequr Rahman is an Associate Professor of Mechanical Engineering Department of Georgia Southern University. He has BS and two MS degrees in Mechanical Engineering. He has received his PhD from the University of Alabama, Tuscaloosa in 2005. He has over 12 years of teaching and over 17 years of research experiences. His research interests' areas are computational and experimental Fluid Dynamics, Wind Energy, computational and experimental Solid Mechanics, FEA and Advanced Materials. Using his expertise and interest has taken the lead to develop a Wind Energy Research Laboratory, Smart Materials Research Laboratory and Nanofluid Research Laboratory in the department since he join at GSU in 2006. He teaches courses in Fluid Mechanics, Engineering Mechanics, Mechanics of Materials, Energy Science Laboratory course, and Intro to FEA to very diverse students. He has published over 50 journal and conference papers; and developed GSU's Wind Energy Laboratory, used by 5 undergraduate and 5 graduate students. Dr. Rahman has been advisor for 10 Master's theses in the last 10 years; and over his career, he has worked with over 2000 students, including minorities and people with special needs.

Travis Salyers

Mr. Travis is a graduate student of the Mechanical Engineering Department at Georgia Southern University. Has received his B.S. in Mechanical Engineering from Georgia Southern and currently is a Master's candidate on Applied Engineering.

Emile Maroha

Mr. Emile has received his B.S in Physics from University of Burundi in October 2008. He also has received his M.S. in Physics from Clark Atlanta University in May 2014. Currently, Mr. Emile is a graduate student of the Mechanical Engineering Department at Georgia Southern University.