OPTIMIZATION OF MICRO HORIZONTAL AXIS WIND TURBINE BLADE USING COMPUTATIONAL FLUID DYNAMIC ANALYSIS

P. J. MANGA[1], E.W LIKTA[2], R.O AMUSAT[3], S.D BUTEH[4], MUHAMMAD ABUBAKAR[5]

[1-3]Department of Physics, University of Maiduguri, Borno State – Nigeria.
[4]Department of Chemistry, Adamu Tafawa Balewa College of Education Kangere, Bauchi.
[5]Department of Science Laboratory Technology, Abubakar Tatari Ali Polytechnic, Bauchi

ABSTRACT

In this study we optimized the performance of micro horizontal axis wind turbine (HAWT) blade using computational fluid dynamics on the basis of Blade element momentum theory (BEM). A micro horizontal axis wind turbine (HAWT) blade of 1.0m long was design using aerodynamics design parameters such as chord length, lift force, drag force, tip speed ratio, solidity, coefficient of performance, angle of attack, wind relative angle, Reynolds number, efficiency, axial and induction factor were all calculated. The 2D preprocessor Gambit interface was used to generate optimized mesh and boundary conditions for an efficient extraction of kinetic energy of the wind by the optimized blade. The meshed was exported to fluent were it was processed and analyzed based on the boundary conditions as identify on Gambit interface. The simulated blade was design based on average wind speed of 5.3mls measured at 10m height above the ground, which is found to be suitable for some locations in North East, North Central and North West. The results showed that the maximum extractable power was 125.44watts at a relative wind speed (velocity) of 5.3m/s with a Reynolds number of 3.0×10^6 at an optimal lift to drag ratio. It's was also recorded that the increased in wind speed also increase the measured extractable power. The design blade satisfied Newton's third law and Bernoulli's effect at an efficiency of 32.1%. Which has the ability to extract and generate energy from the wind; it is a clean source energy that is freely available throughout year with almost zero emission of greenhouse gases and without seasonal variation. The use of this source of energy will reduce frequent blackout and dependence on importation of fossil fuel which is a huge burden to Nigeria economic.

Keywords: Computational fluid dynamics, aerodynamics, airfoil, horizontal axis wind turbine (HAWT) blade, blade element momentum theory (BEM).

Introduction

The wind of the earth arises as a result of uneven heating and spinning on earth due to temperature difference by the solar radiation. For efficient energy extraction, blades of modern wind turbines are made with airfoil sections. When an airfoil is placed in a wind stream, air passes through both upper and lower surfaces of the blade. Due to the typical curvature of the blade, air passing over the upper surface has to travel more distance per unit time than that passing through the lower side. Thus, the air particles at upper layer move faster (perkins *et, al.,* 1978). According to Bernoulli's theorem, this should create a low pressure region at the top of the airfoil. This pressure difference between the upper and lower surface of airfoil will result in a force (F). The component of this force perpendicular to the direction of the undisturbed flow is called the lift force (L).

The free flowing stream of air possesses kinetic energy which can be extracted and convert into useful from of energy such as electricity. The energy extracting device is called a wind turbine that is a rotor dynamics machine that converts the available fluid stream into mechanical then to electrical energy. There are two types of wind machine which are classified based on their axis of rotation. Horizontal axis wind machine have the axis of rotation of their blades horizontal to the ground and almost parallel to the wind stream on the other hand the wind machine that it axis of rotation and it's blade oriented vertical are called Vertical axis wind turbine (VAWT). Most of the rotor dynamics wind machine used today are horizontal axis wind turbine due to its low Cut_{in} wind speed and the size of the wind machine varies widely. Small turbines used to power a single home or business. Larger turbines are often grouped together into wind farms that provide power to the electrical grid (David wood, 2009).

Horizontal axis wind turbines (HAWT) have the following main parts, a rotor, a generator, gearbox and an electric converter. Each of these components has lesser efficiency. The total efficiency of such a turbine is defined by (David wood, 2009) as:

$$\eta_{total} = \frac{P_{grid}}{P_{max}} = \eta_{rotor}\eta_{gear\ box}\eta_{gen}\eta_{conv}$$

(1)

The rotor of a (HAWT) consists of the blade, hub and the shaft. The blade served as the major part of the wind turbine that converts the kinetic energy of the wind into mechanical then further into electrical energy. In other to extract the maximum kinetic energy of the wind the blade of a wind turbine most be design based on selection of airfoil (geometry). An airfoil is a two dimensional section of the blade whose purposed is to create lift or to minimized drag when exposed to a stream of air (moving fluid). In this study we analyzed the performances of the blade by investigating its aerodynamics behavior according to the design parameters, which include rated wind speed, design tip speed ratio, design angle of attack and design rotor diameter.

Optimization of a wind turbine blade means to optimize it chord length, twist distribution and the selection of airfoil shape. There is vast number of multi-dimensional blade optimization but in the case of this study we used the computational fluid dynamic functions. The aerodynamics performance of a wind turbine blade can be analyzed, evaluate and determined using computational fluid dynamic (CFD), which is a branch of fluid mechanics that employed numerical method and algorithms to analyzed and solved problems related to fluid flow. The blade structural analysis can be achieved through the blade element momentum (BEM), by dividing the blade into number of elements consisting of airfoil cross section.

Computational fluid dynamic (CFD) analysis generated the design blade geometry through the Gambit interface which is a preprocessor of ANSYS fluent. It is a (CFD) software that perform 2D and 3D modeling of mechanical components to be simulated after been design on a solid work or design foil workshop. On the same note the fluent is computational fluid dynamic software used for scientific and engineering design by applying laws of fluid mechanics with the conservation of mass, momentum and energy empirical relation to analyze and to solve scientific and engineering problems without producing a prototype. Solving such equations are almost difficult or not achievable analytical thus the need for computational fluid dynamic (CFD) application (Povl Brondsted *et, al.,* 2013).

Methodology

In this study we design the blade of a micro horizontal axis wind turbine using blade element momentum theory. In this, the blade is said to be divided into multiple of elements, which can stand independently as 2D airfoils. The moment and force can be calculated separately later summed to give the overall forces and moments. The blade design parameters are chord length (C), rotor diameter (D), Blade radial length ($\dot{r}$), blade relative angle $(\emptyset)$, blade span (L), angle of attack (θ), tip speed ratio (λ_r), solidity (σ), lift force (F_L), drag force (F_D), the power coefficient (C_p), turbine blade efficiency (η), axial (a) and $(\dot{a})$ radial induction factors.

The kinetic energy (E) of a stream of air is given by (Willen Nijhoff, 1982) as:

$$E = \frac{1}{2}mv^2 \text{ (kgms}^{-2}\text{)} \quad (2.1)$$

where $m =$ Mass of a stream of air (kg)

$v =$ Velocity of the stream of air (m/s)

Now, the wind stream has total power (P) given by

$$P = \frac{1}{2}\rho_a A_T v^3 \text{ (Wm}^{-2}\text{)} \quad (2.2)$$

where $\rho_a =$ Density of incoming wind, (kg/m^3) which is 1.226 kg/m^3 at 1 atm, 15^{0}C

$A_T =$ Cross-sectional area of the wind rotor (m^2)

The force in the direction of the undisturbed flow is called the drag force (D) (muyiwa Adamamola *et al*, 2014).

The lift force (L) is given by equation (2.8) as:

$$L = c_L \frac{1}{2}\rho_a A v^2 \text{ (kgm/s}^2\text{)} \quad (2.3)$$

Also, the drag force (D) is given by;

$$D = c_D \frac{1}{2}\rho_a v^2 A \text{ (kgm/s}^2\text{)} \quad (2.4)$$

where c_L and c_D are the lift and drag coefficients respectively.

The angle between the undisturbed wind direction and the chord of the airfoil is known as the angle of attack (α) given by equation (2.10) (Peter *et. al*, 2011).as:

$$\alpha = \varphi - \theta \quad (2.10)$$

where θ = angle between the rotor plane and the airfoil chord.

φ = flow angle given by equation (2.11) as:

$$\tan\varphi = \frac{(1-a)V_0}{(1+a\prime)wr} \quad (2.11)$$

where a, a', w and r are the axial induction factor, tangential induction factor, resultant velocity and radial distance of the rotor respectively.
The axial induction factor (a) and radial induction factor ($\dot{a}$) are given by the equation below

$$a = \frac{1}{\frac{4cos\emptyset}{\sigma C_L} - 1} \quad (2.12)$$

$$\dot{a} = \frac{1}{\frac{4Fcos\emptyset}{\sigma C_L}} \quad (2.13)$$

The lift and drag forces experienced by an airfoil is influenced by this angle. The angle of attack (α) has effect on the lift coefficient of an airfoil. At lower angles of attack, the lift force increases with α. The lift reaches its maximum at a certain α for an airfoil (12^0 in this example) and then decreases with further increase in α. This is because, at higher angles of attack, the airflow enters air excessively turbulent region and the boundary layers get separated from the airfoil. At this region, lift force decreases and the drag force is rapidly built up, resulting in the stall of the blade (Perkins *et. al*, 1978).
Also, the lift and drag forces are affected by the Reynolds's number. Reynolds's number is the ratio between gravitational force and the viscous force given by (Perkins *et. al*, 1978) as:

$$R_e = \frac{V.C}{\gamma} \quad (2.12)$$

where V is the flow velocity,

c *is the* Chord length

γ is the Kinematic viscosity of the fluid. For air is 15 X $10^{-6}m^2/s$ at 20^0C.

The chord length (C) is the length from the leading edge to the trailing edge of the a blade cross section that is parallel to the vertical axis symmetry and the relative angle is given as

$$C = \frac{8\pi\dot{r}}{BC_L}(1 - cos\phi) \quad (2.13)$$

$$\phi = \frac{2}{3}tan^{-1}\left(\frac{1}{\lambda_r\left(\frac{\dot{r}}{r}\right)}\right) \quad (2.14)$$

The tip speed ratio (λ_r) is the ratio of the blade tip speed over wind speed. It is a significant parameter for wind turbine design (Sathyajith Mathew, 2011) given by the below equation.

$$\lambda_r = \frac{\omega r}{v} = \frac{2\pi N r}{60v} \quad (2.15)$$

Solidity ratio (σ) is the ratio of the area occupied by the blade to the available free space given by;

$$\sigma = \frac{B \times C}{2\pi r} \quad (2.16)$$

The power coefficients C_p defined as the ratio of the output power produced to the power available in the wind given by equation (2.13) (Thirishwe. Yi, 2007) as:

$$C_p = \frac{2P_T}{\rho_a A_T V^3} = \frac{2}{\rho_a A_T v^3} \int_0^R \Omega 4\grave{a}(1-a)\frac{1}{2}\rho_a v 2\pi dr \quad (2.17)$$

where $A_T =$ Area of the turbine's rotor

$\rho_a =$ Air density (kg/m^3)

$v =$ Air velocity (ms^{-1})

$P_T =$ Power developed by the turbine (Wm^{-2})

In this case, the thrust force (F) experienced by the rotor can be expressed as:

$$F = \frac{1}{2}\rho_a A_T v^2 \text{ (kgms}^{-2}\text{)} \quad (2.14)$$

If the drag force D components is given by the relation:

$$D = C_D \frac{1}{2}\rho_a A_T v^2 \text{ (kgm}^{-2}\text{)} \quad (2.15)$$

where $C_D =$ Drag coefficient given by the relation:

$$C_D = \frac{2D}{\rho_a A_T v^2} \quad (2.16)$$

Betz limit is the theoretical limit assigned to efficiency of a wind turbine. It states that no turbine can convert more than 59.3% of wind kinetic energy into shaft mechanical energy. Thus the value of C_p is limited to Betz limit. For a well-designed turbine the efficiency lies in the range of 35 - 45%. In this case, the maximum theoretical power coefficient of a horizontal axis wind turbine is $\frac{16}{27}$ and the maximum power (P_{Tmax}) produced is given by (David Wood, 2009) as:

$$P_{T\,max} = \frac{1}{2}\rho_a A_T v^3 \frac{16}{27} \text{ (kgms}^{-2}\text{)} \quad (2.17)$$

Therefore the efficiency of the blade on the wind turbine is given by;

$$\eta = \frac{C_p \times 27}{16} \tag{2.18}$$

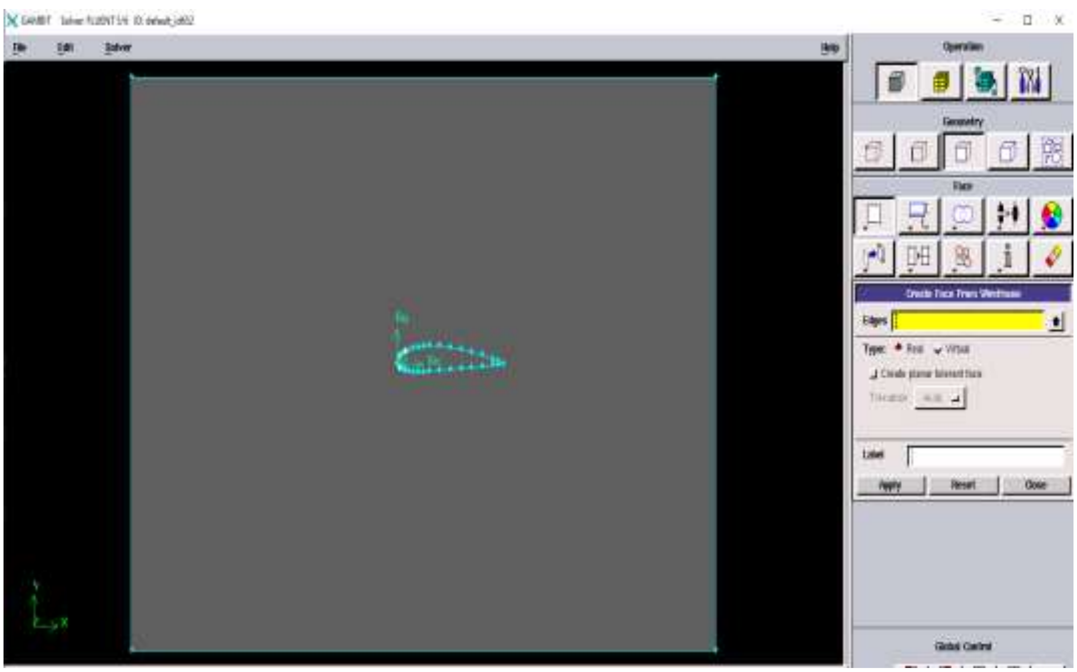
The speed at which the wind is blowing most of the time is given by the modal speed, Vmode is given by equation (2.19).

$$V_{mode} = c(\frac{k-1}{k})^{\frac{1}{k}},\ k > 1 \tag{2.19}$$

The most probable (V_{mp}), maximum energy carrying for Weibull distribution can be expressed as

$$V_{mp} = c(\frac{k+2}{k})^{\frac{1}{k}},\ k > 1 \tag{2.20}$$

A Computational fluid dynamic (CFD) give us the room to investigate the viability of the blade using Gambit and Fluent where the blade design is carry out and also analyzed. On the same note the computational domain of Gambit interface give us the 2D geometry of the blade. The domain was mesh and boundaries selected with



The mesh was exported to Fluent 6.2 where it was later subjected to some fundamental law of fluid mechanics and the conservation of mass and momentum were analyzed and solved based on CFD Navier Stokes system of equations such as continuity equation, momentum equation and equation given by.
Continuity Equation is given by;

$$\frac{\partial p}{\partial p} + \nabla.(\rho\overrightarrow{V}) = 0 \tag{2.21}$$

x −Component momentum equation is given by

$$\frac{\partial(pu)}{\partial t}+\nabla.\left(\rho u\vec{V}\right)=-\frac{\partial p}{\partial x}+\rho f_x \tag{2.22}$$

y −Component momentum equation is given by

$$\frac{\partial(pv)}{\partial t}+\nabla.\left(\rho v\vec{V}\right)=-\frac{\partial p}{\partial y}+\rho f_y \tag{2.23}$$

The 2D energy equation is given by

$$\rho\dot{q}-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}+\rho\vec{f}.\vec{V} \tag{2.24}$$

Results and Discussion

Maiduguri climate parameter was used to carry out the simulation. The continuum used is air to analyze its flow structure over 2D airfoil with the following properties under a given set operating conditions at Atmospheric Pressure of 101325 Pascal and Atmospheric Temperature of 308K.

Table 1: Properties of the continuum used

Property	**Units**	**Method**	**Value (s)**
Density	kgm^3	Constant	1.223
Cp (Specific Heat)	j/kgk^{-1}	Constant	1006.43
Thermal Conductivity	w/mk^{-1}	Constant	0.0242
Viscosity	kg/ms^{-1}	Constant	1.7894e-05
Molecular Weight	$kg/kgmol$	Constant	28.898
L-J Characteristic Length	$angstrom$	Constant	3.699
L-J Energy parameter	k	Constant	79.56

The spalart-Allmaras viscous models under the boundary condition and discretization scheme as shown in table 1 and table 3.

Table 2: Boundary conditions

Zones name	**id**	**Type**
Fluid	2	Fluid
Wall A	5	Wall
Wall B	5	Symmetry
Farfield_1	4	Pressure outlet
Farfield_2	7	Velocity inlet
Default-interior	9	Interior

Table 3: Discretization scheme

Variable	Scheme
Pressure	Standard
Momentum	First Order Upwind
Modified turbulent viscosity	First Order Upwind
Energy	First Order Upwind

At 8^0 angle of attack the 2D airfoil was subjected to the conditions as it is in table 1, table 2 and table 3. The simulation results revealed the air flow contours of velocity and pressure distribution of Spalart-Allmaras viscous models as shown in figure 1-2.

Fig 1: Air flow contour of velocity for Maiduguri

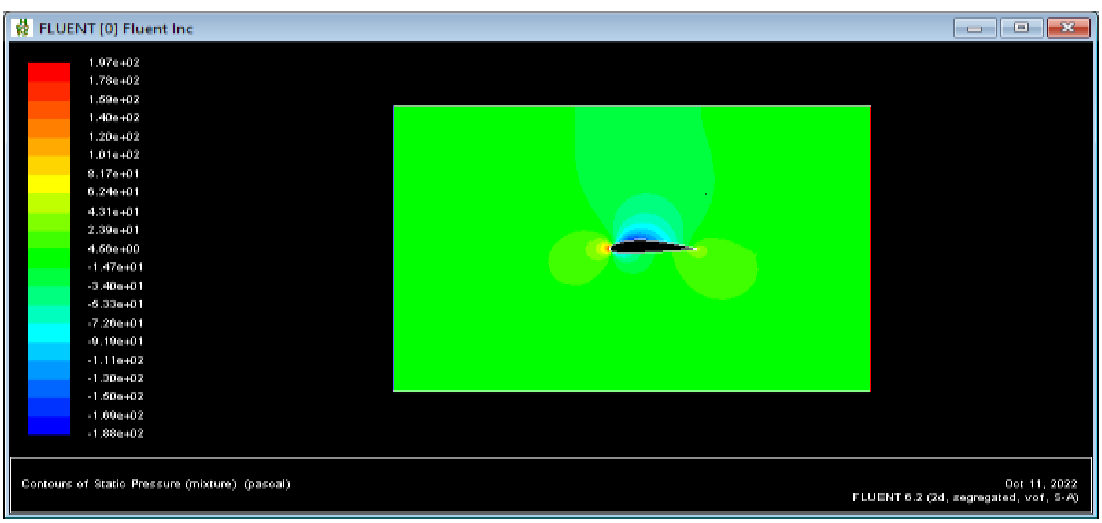


Fig 2: Air flow contour of pressure on 2D airfoil for Maiduguri

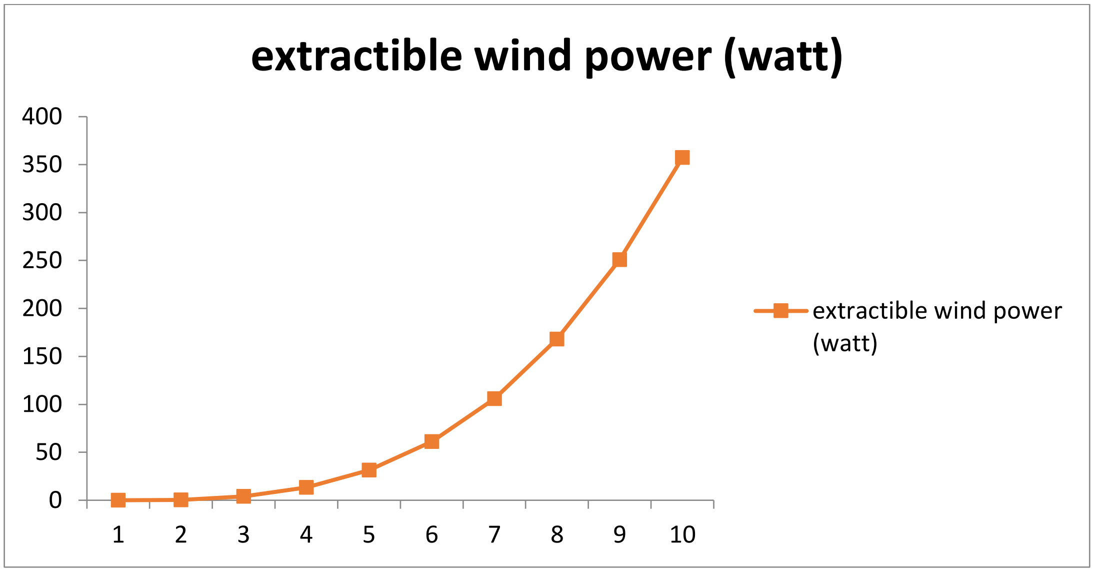


Fig3; Extractible wind power in (watts) for Maiduguri Metropolis at a varying wind speed (m/s)

Figure 1 and 2 show the pressure and velocity distribution on the airfoil surface. The side where the airfoil experience high pressure result into higher lift than drag, the head of the airfoil is expose to low pressure and high velocity zone thus allowing the higher air velocity to drive the optimized blade. Similarly a negligible air pressure experience at the tail of the airfoil. The selected airfoil is in conformity with NACA airfoil 4418 which have suitable lift to drag ratio. On the same note, the result satisfies Bernoulli Effect and Newton's third law.
The extractible wind power based on the velocity distribution is shown in figure 3. Whereas the higher the velocity the greater the power that will be extracted by the turbine blade.

Conclusion

The profile of a wind turbine blade has been designed and the airfoil geometry was created in 2D Gambit interface. Computational fluid dynamic (CFD) code fluent 6.3 is selected to mesh the airfoil boundary and its simulation. The blade design criteria were experimentally verified by testing the physical built blade and the results was compared with that of the iteratively simulated CFD model. A wind speed of 5.3 m/s simulation results shows a power output of 101.98 watts at a suitable lift to drag ratio, generated at 8^0 angle of attack. There is a good correlation between experimental and simulated results. At a wind speed of 5.3m/s the simulated power output is recorded as 108.29 watts. While that of the experimental power output is 101.98watts. Therefore the optimized airfoil will enhance the efficiency of the turbine blade through power extraction and energy generation from local wind availability within Maiduguri and it's environ.

References

Thiri Shwe Yi Win, "Design and performance analysis of wind turbine", Ph.d Thesis, MTU, Myanmar, 2007.
David Wood, "Small Wind Turbines, Analysis, Design, and Application", Department of Mechanical Engineering, University of Calgary, Canada 2009.

Sathyajith Mathew, "Wind Energy, Fundamentals, Resource Analysis and Economics" in India, 2006. Grant Ingram, "Wind Turbine Blade Analysis using the Blade Element Momentum Method", Version 1.1 in October 18, 2011.

Perkins, F.W and Cromack, Duane E, "Wind Turbine Blade Stress Analysis and Natural Frequencies", Wind Energy Center, University of Massachusetts, USA, 1978.

Peter Jamieson, Garrad Hassan, "Innovation in Wind Turbine Design", UK, 2011. [7] R. Nolan Clark, "Small Wind – Planning and Building Successful Installations", USA, 2014.

Muyiwa Adaramola, "Wind Turbine TechnologyPrinciple and Design", Nigeria, 2014.

Willem Nijhoff, "Syllabus for Irrigation with Windmills Technical Aspects", Technical Development with Developing Countries, Netherlands, January, 1982.

Povl Brondsted and P. L. Nijssen, "Advances in Wind Turbine Blade Design and Materials", UK, 2013. Bharath Koratagere Srinivasa Raju, "Design Optimization of a Wind Turbine Blade", USA, 2011