



PERFORMANCE OF A PROTOTYPE WINDMILL FOR WATER PUMPING IN KPAKUNGU COMMUNITY OF NIGER STATE, NIGERIA

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ABSTRACT

Water is the primary source of life for mankind and one of the most basic necessities for rural development. Most rural communities in Nigeria do not have access to potable water. This research considers the provision of water to a community in Nigeria using power from wind. The design results show that a 2.076m diameter windmill is required for pumping water from borehole through a total head of 45m to meet a daily demand of 3.5m³ of water. Performance test of the horizontal axis wind pump was carried out. The lowest measured wind speed during the test was 0.4 m/s, while the corresponding water discharge flowrate was 0.032 l/s. The highest flowrate of 0.113 l/s was recorded at a wind speed of 2.4 m/s. Computer simulation was carried out to validate the performance test of the prototype windmill. The results showed that water discharge is proportional to the wind speed.

Keywords: Energy, Kpakungu, mean wind speed, plunger, windmill.

1. INTRODUCTION

The rising global energy demand and overdependence on fossil fuels have been the main drivers of climate change. According to the United Nations report, the world population is estimated to hit 10 billion by 2050 [1] to meet the energy needs of this population, energy production must double. However, greenhouse gas emission must be reduced by about 80% to minimize the effect of global warming on the climate. If the conventional means of producing energy are sustained, there will be dire consequences on humans and the environment [2]. A lot of communities in Nigeria still lack adequate supply of potable water. Yet many of these villages especially in the mountainous areas of the Northern region have good wind potentials. Wind, which is a natural and renewable resource, has over the years been discovered has a very reliable source of energy. The objective of the paper is to assess the feasibility of deploying low-cost wind pumps for rural water supply.

Water supply to rural communities is very vital to enhancing effective public health, but energy is also required to achieve this [3]. In most of these communities, self-sourced water sources such as streams, ponds, wells and rivers are used for agricultural purposes [4]. These rural villages are faced with acute shortage power supply; hence they are faced with lots of challenges in transporting water from sources to their farms. As one of the significant sources of renewable energy, wind energy can be deployed for water pumping in these localities. A wind pump is considered as a type of windmill used for pumping water [5]. Literature studies and statistics indicate that the production of mechanical energy and electrical energy from wind turbines has become commercially viable [4].

Wind energy as an option is sustainable with zero emission technology. Surveys on water pumping technologies in India, Sri Lanka, Colombia, Kenya and Zimbabwe have pointed out that wind pumps are generally far cheaper than any other pumping alternative diesel or photovoltaic in particular [6].

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1.1. Background of Drinking Water Situation in the Study Area

Several researchers have conducted studies on the potentials of Renewable Energy Resources for different parts of Nigeria. This study focuses on the potentials of Wind Energy as a cheap source of Energy for water pumping operations in Kpakungu community of Minna, Niger State. In a research conducted by Adeleye B. *et al* [7], the inhabitants of Kpakungu have very poor access to potable water and good sanitation. The study showed that while 60% of the residents of the community have access to pipe borne water, only 20% of the population has constant supply [7,8]. Kpakungu is a rural settlement in Bosso Local Government Area (LGA) of Niger State. It is situated on Latitude 9° 35'55.00" and Longitude 6° 32'00.00". Most of the inhabitants are illiterate with a very low level of education and are generally restricted to alternative water sources because of irregular and unreliable sources from the public mains. Adeleye B. *et al* [7], further reported that 20% of the settlers get their domestic water from water tankers, 18% from vendors who hawk water in plastic containers using 2-wheel carts. 36% get their water from dugout wells, another 18% from boreholes and 8% from streams.

2. MATERIALS AND METHODS

2.1. Materials

The materials and equipment used in this work are steel pipes, PVC pipes, steel sheets, iron rods, radial ball bearings, screws and nuts, flat iron bar, iron flange, digital anemometer, measuring cylinder,

welding machine, drilling machine, cutting machine and grinder.

2.2. Design Theory

In this section, the theoretical basis on which the design was developed is discussed.

2.2.1 Initial Design Data

According to Nigeria Meteorological Agency (NIMET), mean wind speed in Minna is in the range of 1m/s and 4m/s, while the atmospheric temperature for Minna is in the range of 24°C and 42°C.

Proposed volume flowrate of the pump, Q can be obtained from the following:

Estimated number of people = 35

Consumption per capita per day is obtained from Table 1 as 91 litres

Table 1: Provision of cold water storage to cover 24-hour water supply [9]

Type of building	Storage per person (litres)
Dwelling houses and flats	91
Hostels	91
Hotels	136
Offices without canteens	37
Offices with canteens	45
Restaurant per meal	7
Day schools	27
Boarding schools	91
Nurses' homes and medical quarters	114

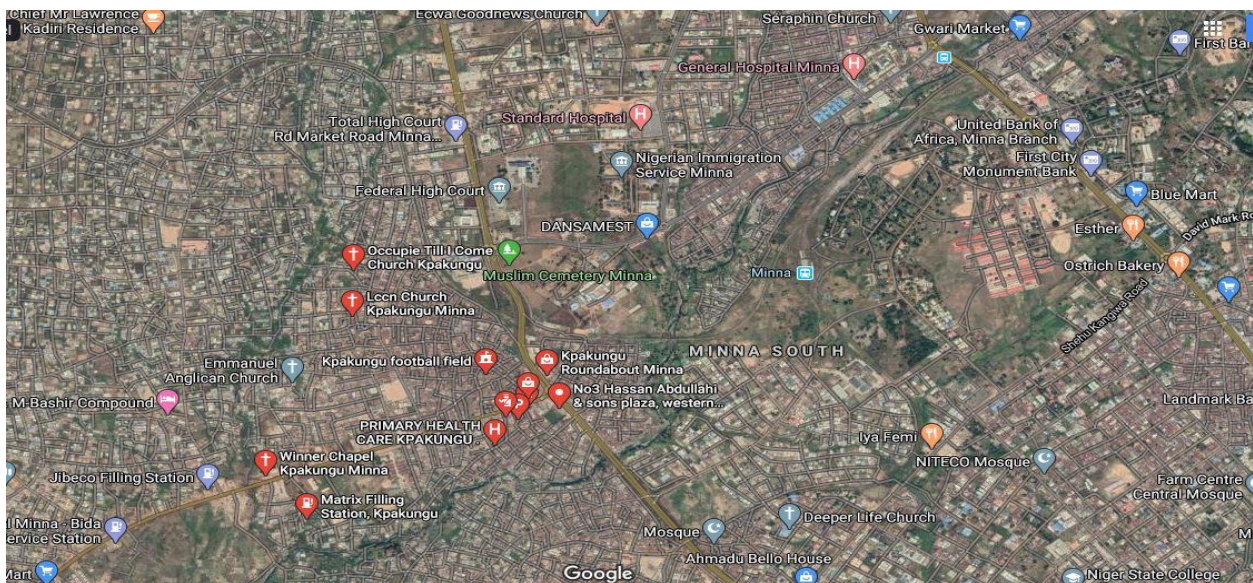


Figure 1: Google image of Kpakungu, Minna, Niger State

2.2.1. Determination of water flow rate and hydraulic power of the pump

Before determining the rotor size, the pump specification in terms of flowrate and power must be calculated:

Storage required for one day = 91 x 35 = 3,185 litres, a 3,500litres tank will be sufficient for one day storage.

The tank is expected to be filled in 4hours.

To obtain the flowrate,

$$Q = \frac{N \times C}{T} \tag{1}$$

Where, N is number of people, C is storage per capita in m³, T is time taken to fill up the tank.

$$Q = \frac{35 \times 91}{4 \times 3600 \times 1000} = 0.221 \times 10^{-3} \text{m}^3\text{s}^{-1} = 0.221 \text{ l/s}$$

Static head of pump or discharge head, H = 4.5m (vertical height of discharge tank)

Acceleration due to gravity, g = 9.81m/s

Power required to pump water (hydraulic power) is obtained from equation (1):

$$P_h = \rho gQH \text{ (W)} \tag{2}$$

Where, ρ = ρ_w = density of water 1000kgm⁻³ P_h = 9.80W

2.2.2. Determination of power extractable from wind and rotor diameter

The rotor consists of blades mounted on a circular disc. The important parameters in determining the rotor size are enumerated and discussed in the following texts.

The swept area, A_s, of the rotor is the plane of wind intersected by the blades of the generator.

The swept area for a horizontal axis wind turbine (HAWT) is calculated by:

$$A_s = \frac{1}{4} \pi D^2 \tag{3}$$

Where, windmill power extracted, P_w = P_t x C_p

$$P_w = \frac{1}{2} \rho A V^3 \times C_p \text{ (Watts)} \tag{4}$$

Rotor power:

From equation (4), the extractable power from the wind, which is also known as the theoretical power in the wind or the available power of the wind turbine blade (W)

$$P_{avail} = H_t = \frac{1}{2} \rho_a A V^3 C_p$$

Where, ρ_a = density of air, A = swept area, V = wind speed = 3.0ms⁻¹; C_p = power coefficient

Coupling the Pump to the Rotor:

Sizing of the wind pump is a function of the pump head, hence the power available in the wind can be

obtained from the power required to pump water, P_h or hydraulic power.

However, to obtain the power extractable from the wind, different losses in the system need to be considered. Table 2 shows the various losses:

Table 2: Power losses in a windmill [10]

Factor	Typical efficiency
Rotor to shaft	92-97%
Shaft to gear box	93-96%
Gear box	99%
Pump	60-75%

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}} \times 100\%$$

The power input to the system before losses can be given by:

$$\text{Input power} = \frac{\text{output power}}{\text{efficiency}} \times 100\%$$

Using all efficiencies, power availability was calculated as:

P_{avail} = 16.131W – amount of power extractable from the wind, P_T.

Recall that power coefficient, C_p is the ratio of power extracted by the windmill to the total contained in the wind resource, and can be obtained from the expression:

$$C_p = \frac{P_w}{P_t} = \frac{P_w}{0.125 \rho \pi D^2 V^3} \tag{5}$$

Thus, windmill power extracted, P_w = P_t x C_p, = 1/2ρAV³ x C_p (W). ρ = ρ_a = density of air.

The maximum possible value of C_p is 16/27 at a maximum efficiency of 59%, according to Betz Limit. 0.3 was adopted as the maximum value of C_p [11].

Atmospheric air conditions:

Mean wind speed = 3.0ms⁻¹

Mean temperature = $\frac{24 + 32}{2} = 28^\circ\text{C} = 301\text{K}$

Pressure = 1.02bar

Density of air at 310K and 1.02bar is approximately 1.177kgm³ [12].

P_T = 1/2ρAV³ x C_p, 16.131 = 1/2 x 1.177 x A x 3³ x 0.3 = 4.767 x A

A = $\frac{16.131}{4.767} = 3.384\text{m}^2$. Also, A = 1/4πD²

Hence, Diameter of rotor, D = 2.076m

2.2.3. Determination of Rotor Solidity

Solidity is the percentage of the circumference of the rotor which contains material rather than air. It may be described as the proportion of a windmill rotor’s swept area that is filled with solid blades. Mathematically,

$$\sigma = \frac{NA_B}{A_s} \tag{6}$$

The Solidity of the rotor assembly can be obtained from equation 6:

Where,

N – Number of Blades = 5

A_B – Area of one blade (m²)

A_S – Swept Area (m²)

$$A_B = \frac{1}{2} \times (A + B) \times L = \frac{1}{2} \times (0.35 + 0.152) \times 1.038 = 0.261\text{m}^2$$

$$A_S = 3.385\text{m}^2; \text{Solidity} = 0.386$$

2.2.4. Shaft design

Determination of shaft diameter

Force exerted on shaft can be obtained from:

$$F = \frac{1}{2} \times \rho \times A \times V^2 \tag{7}$$

$$F = 0.5 \times 1.177 \times 3.385 \times 3^2 = 17.93 \text{ N}$$

The torque acting on the shaft can be obtained from:

$$T = F \times \frac{D}{2} \tag{8}$$

$$T = 17.93 \times \frac{2076}{2} = 18,611.34 \text{ N-mm}$$

To determine the shaft diameter, the following expression was used:

$$T = \frac{\pi}{16} \times \tau \times d^3 \tag{9}$$

$$18611.34 = \frac{\pi}{16} \times 55 \times d^3 \text{ or}$$

$$d = 11.99\text{mm,}$$

Commercially available shaft diameter of 15 mm was adopted.

Determination of load ratings and diameters of bearing

The diameter of the shaft was used as the bore of the bearings, the bore is 15 mm. For a radial ball bearing with a 15 mm bore, the corresponding bearing no. is either 202 or 302 [11]. While the outside diameter for bearing no. 202 is 35 mm, that

of 302 is 42 mm. 302 was selected. The static and dynamic loads for the selected bearing are 5.20 and 8.80 respectively [11].

$$C_0 = 5.2\text{kN}, C = 8.8\text{kN}$$

From equations (26) and (27)

$$C = W \left(\frac{L}{10^6} \right)^{1/3} \tag{10}$$

$$\text{Also, } L = 60 \times N \times L_H, N = \frac{\lambda \times V}{\pi \times D} \times 60$$

$$\tag{11}$$

$$\text{Optimal tip speed ratio, } \lambda = \frac{4\pi}{n} = 2.5$$

$$N = 69 \text{ rpm, } L_H = 40,000 \text{ hours}$$

$$L = 165.5 \times 10^6 \text{ rev, } C = W \times (165.5)^{1/3}, W = 1.6\text{kN}$$

Equivalent dynamic load rating, W = 1.6kN

Basic dynamic load rating, C = 8.8kN

Bore of bearing = 15mm

Outer diameter = 42mm

2.3. Windmill Simulation

Solidworks was used to carry out the simulation. The SolidWorks 2017 software icon was clicked on the desktop menu on the window interface and a new part was clicked on followed by clicking on the sketch tab which activated all the design tools which were used to design the blades, rotor hub, tower, plunger and cylinder, crank mechanism, blade disc shown in Figures 4, and 6. Each component was developed by selecting a solid shade from the tool bar; dimensions and angles of orientation were chosen, and the software modelled the desired component. After the completion of the design of each part, exit sketch was clicked on the window interface and design tools were deactivated.

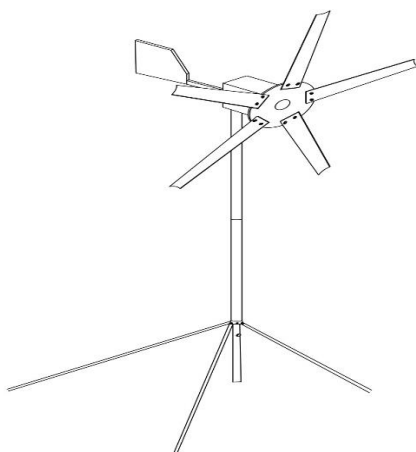


Figure 2: Windmill isometric drawing

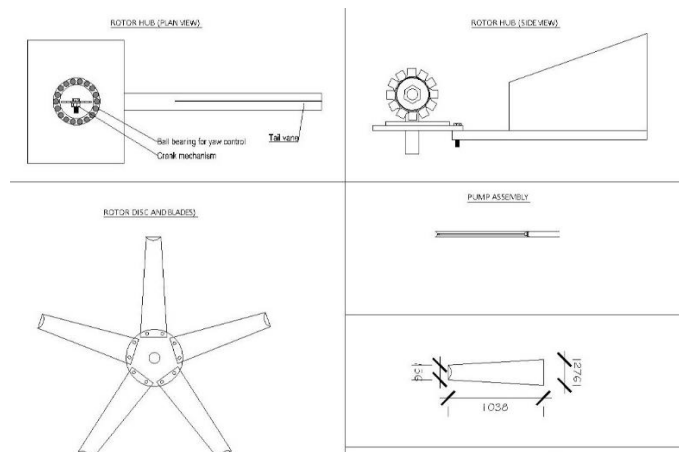


Figure 3: Components of the windmill

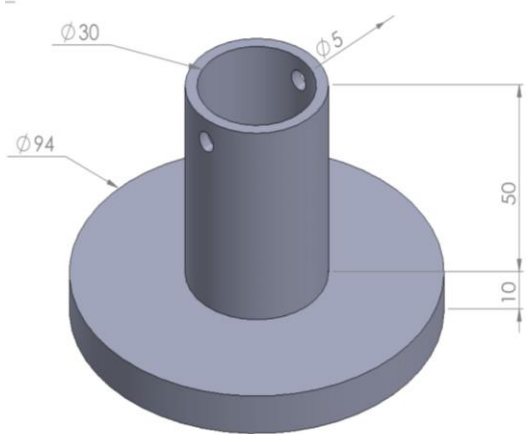


Figure 4: Plunger

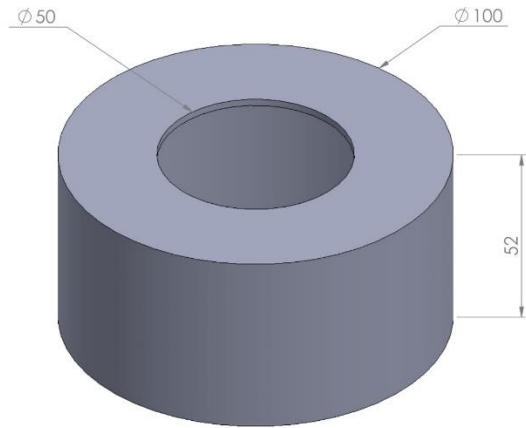


Figure 5: Cylinder

The modelled components were assembled using the assembly tool in the software, Figure 7. The flow simulation tab was checked and all the tools required for simulation were activated and displayed. So wizard option was clicked on and activated a pop-up window. A new project option was clicked on and selection of simulation parameters were displayed. The simulation was carried out using a wind tunnel shaped in cuboid form, and internal flow analysis was carried out on the model to obtain required result. Since an internal flow analysis was carried out with the aid of a wind tunnel, the major effect that was considered was the effect of the wind speed and direction on the rotor speed (in revolutions per minute) and wind blades velocity and pressure. The design wind speed for the fabricated wind pump,

which is 3 m/s, was used as the boundary condition (base speed) for simulation.

2.4. Performance Evaluation

The windmill was set up for testing at an open field near the workshop of the National Incubation Centre, Tunga, a suburb of Minna in Niger State, Nigeria. A digital anemometer (Mastercool 52236 Airflow Psychrometer) was used to measure the windspeed, relative humidity, dry bulb and wet bulb temperatures. The strobe of the anemometer was further connected to the rotor hub to obtain the rotor speed in revolutions per minute. The test was carried out to determine the quantity of water discharged at different wind speeds at a given time duration.



Figure 6: Components of the windmill.



Figure 7: Complete windmill model

3. RESULTS AND DISCUSSION

3.1. Experimental Result

The variation of water discharge (in litres) with wind speed for Day 1 of the experimental tests is shown in Figure 8.

It can be seen from Figure 8 that as wind speed increases, the volume of water discharged increases. The maximum water discharge of 14.09litres was obtained at the maximum wind speed reading of 1.92 m/s. The chart indicates a direct relationship between wind speed and the volume of water discharged. The result is in line with the results obtained by Odesola & Adinoyi (2017), they carried out pump performance tests on their fabricated wind powered water pump. The maximum windspeed they recorded on the first day was 2.10 m/s, and the corresponding water discharge was 7.81 litres. The difference in output is because of the difference in design considerations, their design wind speed was 2.5 m/s. Table 3 provides the corresponding Dry Bulb Temperature and Relative Humidity readings at the various measured Wind Speeds on the Day 1 of the performance test.

The variation of water discharge (in litres) with wind speed for the test carried out on Day 2 is depicted in Figure 9.

It can be seen from the performance test carried out on the second day, that the highest water discharge of 13.22 litres was achieved at the maximum wind speed of 2.03 m/s, while the least

discharge of 5.44 litres was obtained at the lowest wind speed of 0.56 m/s. The readings obtained on Day 2 of the experimental test indicated that Wind Speed has no direct impact implication on either the Dry Bulb Temperature or the Relative Humidity as depicted in Table 4. The variation of water discharge (in litres) with wind speed for the test carried out on Day 3 is shown in Figure 10.

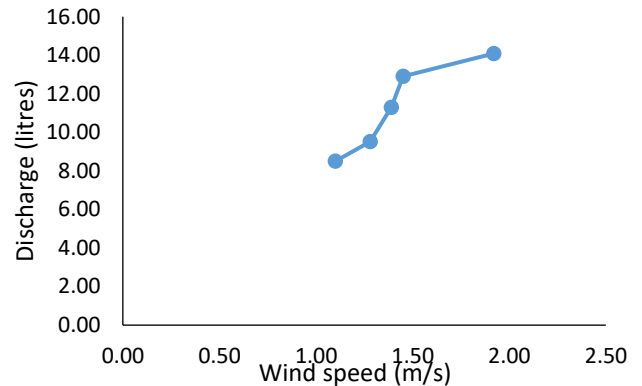


Figure 8: Variation of water discharge with wind speed. Day 1

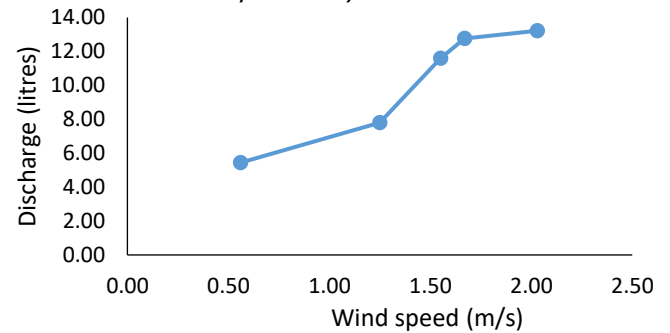


Figure 9. Variation of water discharge with wind speed. Day 2

Table 3: Test result for wind pump performance. Day 1

Duration of test (mins)	Measured Wind speed (m/s)	Water discharge (litres)	Rotor / blade speed (RPM)	Measured Dry Bulb Temperature (°C)	Measured Relative Humidity (%)	Calculated flowrate (litres/sec)
00:00	0.00	0.00	0.00	0.00	0.00	0.00
05:00	1.28	9.52	13.4	25.3	33.5	0.096
10:00	1.92	14.09	19.2	31.5	20.2	0.117
15:00	1.39	11.29	14.8	37.1	12	0.111
20:00	1.10	8.50	11.6	36.8	12.8	0.071
25:00	1.51	12.90	16.8	23	34	0.108

Table 4: Test result for wind pump performance. Day 2.

Duration of test (mins)	Measured Wind speed (m/s)	Water discharge (litres)	Rotor / blade speed (RPM)	Measured Dry Bulb Temperature (°C)	Measured Relative Humidity (%)	Calculated flowrate (litres/sec)
00:00	0.00	0.00	0.00	0.00	0.00	0.00
05:00	1.67	12.76	17.6	26.5	44.8	0.081
10:00	2.03	13.22	21.43	32.4	35.2	0.111
15:00	1.25	7.80	12.5	38.5	23.0	0.074
20:00	0.56	5.44	6.4	37.6	21.5	0.045
25:00	1.55	11.59	16.4	35.0	27.6	0.105

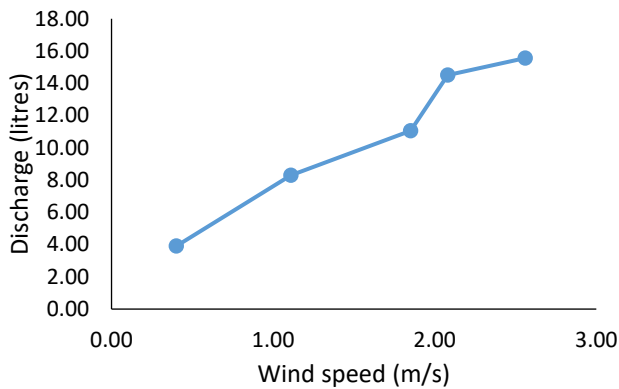


Figure 10. Variation of water discharge with wind speed. Day 3

As observed during the experiment in the previous days, figure 10 depicts that at the maximum wind speed of 2.54 m/s, the largest water discharge of 15.56 litres was achieved. Also, at the lowest wind speed of 0.40 m/s, the least water discharge of 3.90 litres was measured. The results can be compared with the results obtained by [13,14], in both works, the researchers concluded that output of a windmill operated water pump depended on the wind speed. Table 5 shows the result of other parameters measured during the test on Day 3.

3.2. Simulation Result

The flow trajectory for velocity of the windmill obtained during simulation using solid works flow 2017 is shown in Figure 11. It was further established that the colour variation represents the fluctuation of the magnitude of the wind velocity that is depict sudden increase and rapid decrease in the velocity of the wind around the blades. Wind approaches the blades at higher speed but reduces rapidly to a momentary 0 m/s as it strikes the blades. But the magnitude of the wind speed again rises gradually as air leaves the blades. The energy of the wind is transferred to the blades, this in turn, causes rotation of the blades. The energy lost by the wind gives power to rotate the rotor and produce a reciprocating motion of the plunger pump. The simulation result also showed the normal force, minimum force and torque acting on the blades. The maximum values of

the normal force, minimum force and torque are 0.57 N, 0.0 N and 0.053 Nm. The maximum rotor speed was observed at the highest air velocity, this further confirms that rotor speed is directly proportional to wind speed, if the system is correctly designed. The summary of the result obtained during simulation is shown in Figure 12.

3.3. Comparison between Experimental and Simulation Result

The experimental result of the newly designed windmill was compared with the simulation result of the computer model. The rotor speeds in RPM for the two tests are provided in Figure 13.

As seen in Figure 13, the rotor speed increases as the velocity of the wind increases. At a maximum wind velocity of 2.8 m/s, the rotor speed obtained during simulation of the model was 22.49 RPM. While at the maximum wind velocity of 2.54 m/s measured during experimental test, the rotor speed was 23.62 RPM. The rotor speed for the experimental test increases more in magnitude than the simulated rotor speed, despite lower wind speeds of the experimental.

The simulation result provides a more perfect straight-line gradient than the experimental result. However, they both have similar behavior.

4. CONCLUSION

Based on the performance evaluation, the design and fabrication of a prototype windmill for water pumping in rural communities of Niger State which operates on the principle of converting the rotational motion of the rotor into reciprocating motion of a pump were achieved. It can be concluded that it is feasible to use wind energy to pump water in rural communities of Northern Nigeria. It can be further concluded that the output and performance of a correctly designed windmill depend on the wind speed, because the wind speed determines the power that can be extracted from the wind in the form of rotational motion of the rotor and blades.

Table 5: Test result for wind pump performance. Day 3

Local time	Measured Wind speed (m/s)	Water discharge (litres)	Rotor / blade speed (RPM)	Measured Dry Bulb Temperature (°C)	Measured Relative Humidity (%)	Calculated flowrate (litres/sec)
00:00	0.00	0.00	0.00	0.00	0.00	0.00
05:00	1.41	11.05	13.8	26.2	30.7	0.077
10:00	2.54	15.56	23.62	32.0	20.3	0.113
15:00	1.11	8.30	12.4	36.5	11.0	0.092
20:00	0.40	3.90	5.3	38.9	10.2	0.032

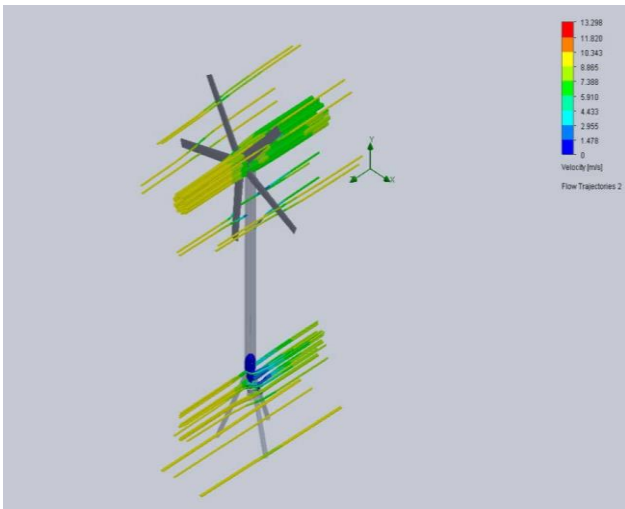


Figure 11. Flow trajectory for wind velocity

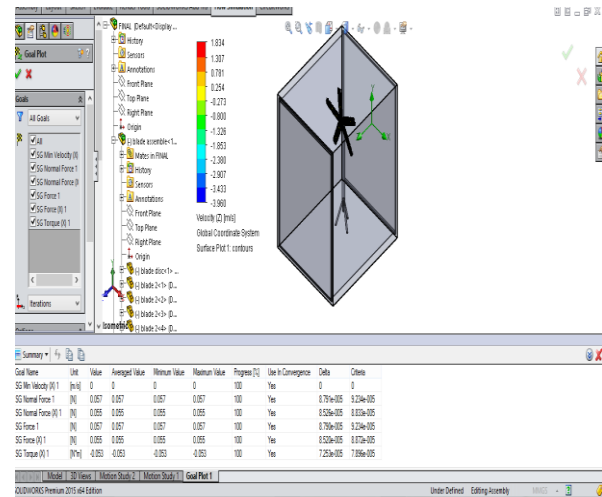


Figure 12: Simulation of Windmill in a Wind Tunnel

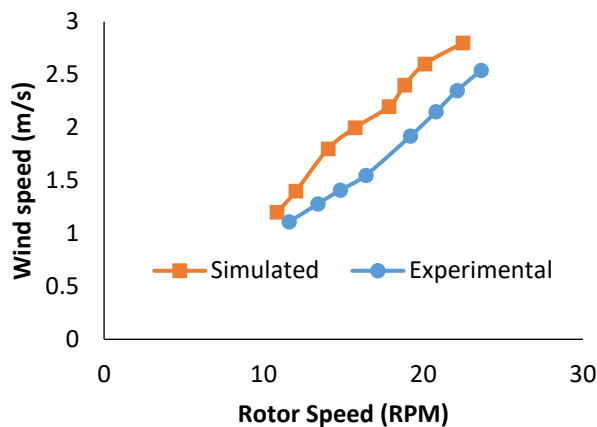


Figure 13: Variation of Wind Speed with Rotor Speed

5. REFERENCES

- [1] Population Division UNDESA. World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. United Nations Dep Econ Soc Aff 2017. <https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html> (accessed October 7, 2018).
- [2] Green Cross International. Smart Energy 2018. <https://www.gcint.org/smart-energy/> (accessed November 2, 2018).
- [3] Ahmmed S. Investigation And Analysis of Wind Pumping System for Irrigation in Bangladesh. Bangladesh University of Engineering and Technology, Dhaka, 2002.
- [4] Vani R, Mutalikdesai S, Sowjanya B, Kumar A. Design and Fabrication of Vertical Axis Wind Turbine for Water Pump Application. *J Mech Eng Autom* 2017;7:95–8. doi:10.5923/j.jmea.20170704.01.
- [5] Greenhalgh A. Water. BBC Heal 2007. https://web.archive.org/web/20070101100025/http://www.bbc.co.uk/health/healthy_living/nutrition/drinks_water.shtml (accessed November 2, 2018).
- [6] Siddig MH. The feasibility of using wind-pumps in Zimbabwe. *Wind Eng* 1997;21:227–36.
- [7] Adeleye B, Medayese S, Okelola O. Problems of water supply and sanitation in Kpakungu area of Minna. *J Cult Polit Innov* 2014;1:1–23.
- [8] Adegbehin A, Yusuf Y, Anumonye E, Shehu A. Problems of Domestic Water Supply in Dutsen Kura Gwari, Chanchaga Local Government Area of Niger State, Nigeria. *J Geogr Environ Earth Sci Int* 2016;7:1–9.
- [9] Hall F. *Design Calculations for Plumbing and Heating Engineers*. Longman Scientific & Technical; 1988.
- [10] Mercyline MN, Mokaya OJ. *Design of a Windmill for Pumping Water*. University of Nairobi, 2009.
- [11] Khurmi R., Gupta J. A Textbook of Machine Design. S.I Units. S. Chand and Company Ltd; 2005.
- [12] Rogers GFC, Mayhew YR. *Thermodynamic and Transport Properties of Fluids*. Fifth. 350 Main Street, Malden, MA 02148-5020, USA: Blackwell Publishing Ltd; 1995.
- [13] Odesola IF, Adinoyi LG. Development of Wind Powered Water Pump. *Int J Eng Sci Comput* 2017;7:10341–5.
- [14] Prasad V, Swami M, Tambe V, Kamate F, Bagade S. Wind Operated Water Pump. *Int Res J Eng Technol* 2016;3:1433–7.