Design of Circular Arc Blade Hydrokinetic Turbine—A Case of Rural Electrification in Zambia

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Abstract

The rate of electrification in rural areas in Zambia is very low, currently standing at less than 5% despite having abundant flowing water resources. Hydrokinetic technology is an alternative among other promising technologies for rural area electrification because of availability of abundant flowing Rivers and low population in rural settlement. In this paper, the author designed and numerically simulated a circular arc blade hydrokinetic turbine system. The design power for the horizontal axis hydrokinetic turbine was 3 kW at water velocity of 3 m/s with the tip speed ratio of 2.5, angle of attack of 10 degrees and power coefficient of 0.4. In this work, a numerical simulation was employed to characterize and develop the horizontal axis hydrokinetic turbine. The prototype circular arc blade horizontal axis hydrokinetic turbine was tested in one of stream in Zambia and the results were compared with the numerical simulation results.

Keywords

Horizontal Axis Hydrokinetic Turbine, Tip Speed Ratio, Power Coefficient, Circular Arc Profile

1. Introduction

The major source of energy for Zambia includes electricity, petroleum, coal, biomass, and renewable energy. The country imports all of its petroleum, but it is also self-sufficient in the other energy resources, because it has good amount of unused reserves of these forms of energy. According to Zambia Development Agency report, it shows that "the country's economy has been growing at an average of 5 percent per annum over the past 10 years and demand for energy has

also been rising. The demand for the most important energy source in the country-electricity has been growing at an average of about 3 percent per annum mainly due to the increased economic activity in the country especially in the agriculture, manufacturing and mining sectors, as well as increased activity in the region" [1]. Furthermore, the growing economy of the country has also caused an increase in the demand for the other forms of energy resources such as coal and petroleum, as these have got major impact production and operations in most economic sectors. In recent years, the energy market has seen significant growth in the demand for renewable energies as an alternative source of energy, and this has proved that renewable energies are the alternative source in that it is environmental friendly [1].

The International Energy Agency (IEA) and the World Bank, both show that the rate of electrification in Zambia stood at 28% in 2014. But the survey conducted in 2015 by the government of Zambia shows the figure of 31%. The rate of electrification in rural areas, as it is the case in most developing countries, is currently much lower at 5% (World Bank) or 4.4% (Government of Zambia). This shows that at least 10 million people or 2 million households do not have access to electricity [2].

Although Zambia is endowed with abundant energy resources, its rural population access rate to electricity is less than 2%. Access to electricity cannot be overlooked as it provides economic development and it also helps in providing energy for irrigation to Zambian farmers. Despite the high demand for electricity in rural areas to sustain pump irrigation farming, the traditional programs by the national utility Zambia Electric Supply Company (ZESCO) for expanding access to electricity through extending the national grid have thus far failed to give significant improvements. In response, the Zambian Government created the Rural Electrification Authority (REA) to carry out innovative approaches to rural electrification and governs the Rural Electricity Fund (REF) [3]. Despite the efforts in improving the rural electrification, there is little progress and success rates, Rural Electrification Master Plan (REMP) targeted 15% rural electrification rate by 2013, but currently, the rural electricity access rate is at 4.4% for grid power and 7.4% for solar power [4]. The technologies currently being employed to promote rural electrification in Zambia include Grid Extension, Mini hydro (from 200 kW to 10 MW) Development, Solar mini-grids, Solar Home System Installations, Biomass and Biogas and Wind [5].

The success rate of most rural areas electrification projects is very low because power generating project requires a large sum of funding to be implemented hence little or no access to electricity in rural areas.

Most of the rural areas in Zambia are situated near or close to flowing water, thus, making the hydrokinetic technology the most economical and reliable option for generating electric power. According to Kamal A.R. Ismail and Tiago P. Batalha, research reveals that most parts of the world are interested in hydrokinetic turbine technology especially in relation to River application [6]. The hy-

drokinetic technology works on the principle of converting the kinetic energy of flowing water into rotational energy by turning the rotor coupled to an electric generator which in turn converts rotational energy into electric energy [6]. In order to produce affordable power for rural communities, the manufacturing cost of the hydrokinetic turbine must below. Tao Bian *et al.* research on flow loss and structure of circular arc blade with different leading edge, where a comparison was made between NACA (National Advisory Committee for Aeronautics) profiles and circular arc blade profiles. The result showed that NACA profiles are able to function and perform better than circular arc blade profile, but the development and production of these profiles are very expensive thus making the circular arc blade profiles an alternative for producing power as their manufacturing cost is very low [7]. Grant Ingram studied wind turbine blade analysis using the blade element momentum method, where Grant showed that for selection of an aero foil for a turbine with the tip speed ratio of less than 3 ($\lambda < 3$), the curved plate or circular arc blade profile can be used rather than an aero foil [8]. Kamal A.R. Ismail and Tiago P. Batalha carried out a comparative study on river hydrokinetic turbine blade profiles, where four geometries were investigated: NACA 0018 profile, NACA 1548 Asymmetric profile, flat plate and circular arc profile. The numerical simulation results showed that the circular arc profile is more efficient and produce more power [6].

This paper focuses on the description of the steps involved in the design and numerical simulation of a small horizontal axis hydrokinetic turbine (circular arc blade profile), comparing the result to a prototype turbine which was tested in one of the Zambian Rivers as the method for generating electrical power for off-grid rural communities in developing countries.

2. Methods and Materials

2.1. Materials

The basis for the material selection is centered on three major factors *i.e.* the bending moment distribution relating to the loads applied on the blades coupled with the turbine operating environment and cost of production. If high bending moments are predicted during operation, then the blade materials should have high specific strength and stiffness for it to retain its shape under high loadings. Since the blade will be immersed in corrosive and erosive water, the current can lead to the material properties being degraded over long periods of time. Thus, the material used should withstand this corrosive and erosive environment while retaining its high strength and stiffness level [9]. In this research, stainless steel was used for the blade with the following mechanical properties as shown in Table 1.

Table 1. Mechanical Properties of the blades [9].

Material	Young Modulus (GPa)	Density (kg/m³)	Poison ratio	Tensile Strength Ultimate/Yield (MPa)
Stainless steel	193	8000	0.3	400/280

2.2. Methods

2.2.1. Hydrodynamic Blade Design

The kinetic energy contained in water by mass, $\dot{m}$ (m/s) with unidirectional and uniform speed V_1 (m/s), is given by Equation (1).

$$E = \frac{1}{2}\dot{m}V_1^2 \tag{1}$$

The mass flow rate through a stationary surface of a control area swept by rotor blade, A ($A = \pi R^2$, where R is the blade radius in (m)), with water density, ρ (997 kg/m³ at 25˚C) is given by Equation (2).

$$\dot{m} = \rho A V_1 \tag{2}$$

On the other hand, the power extracted from a stream of water is calculated using Equation (3).

$$P = \frac{1}{2}\rho A V_1^3 \tag{3}$$

The amount of energy quantity that can be extracted from water, exist in terms of a physical limit and is independent of the design. The amount of energy extraction is maintained in a flow process by reducing the kinetic energy, as a result, the velocity of water reduces. The magnitude of how much energy is harnessed is dependent on the flow speed reduction over the turbine, zero final velocity would imply 100% extraction and therefore, zero flow. It is difficult to achieve zero flow scenario hence all water kinetic energy may not be used up. The wind turbines efficiency has a maximum limit of 59.3% which is widely acceptable for wind turbines. This parameter is commonly known as the power coefficient C_p, where max $C_p = 0.593$ referred to as the Betz limit [9]. This scenario is only experienced when the velocity of the water velocity leaving the turbine is one third of velocity entering the turbine.

On the other hand, the quantity of energy that can be extracted from the water by the hydrokinetic turbine is also reduced by the driver train efficiency, η (generator, gearing, etc.). The value of η is assumed to be 70%, a typical and conservative value for a small turbine for electric generation [10]. Therefore, Equation (3) is modified obtaining Equation (4).

$$P = \frac{1}{2}\rho A V_1^3 C_p \eta \tag{4}$$

According to Kamal *A.* and Tiago *P.* research, it reveals that seven circular arc blades for different values of tip speed ratio have the maximum power coefficient which occurs at tip speed ratio of 2.5 as shown in **Figure 1**.

Assuming that *P* is 3 kW, the water current velocity is 3 m/s, C_p is 0.4 and ρ is 997 kg/m³, the radius of the turbine blades can be calculated using Equation (4). The radius of the blade required is equal to 0.253 m. For simplicity, a blade radius of 0.25 m was used.

2.2.2. Blade Structural Design

Various structural configuration for a curved plate were designed and tested in

ANSYS Fluent but most of the configuration had high flow separation which induced an adverse pressure gradient which greatly reduced the lift force and increased the drag force on the curved blade. The configuration shown in **Figure 2** had low flow separation hence, it was considered as the structural configuration for the hydrokinetic turbine for this research.

The blade shown in **Figure 2** has an angle of attack of 10 degrees and chord length of 0.31 m and **Figure 3** shows the 3D model of the turbine with hub length and diameter of 0.5 m and 0.2 m respectively.

2.3. FEM Analysis

The finite element models (FEM) were developed using the software ANSYS 17.0 academic version through static structural analysis using Mechanical APDL solver. The solid blades and hub of the model had unstructured tetrahedral mesh which converged with 29,427 nodes and 16,489 elements. The hub of the model was treated as a fixed support and all blades were treated as cantilevered beam with all the degrees of freedom being fixed at the hub. The external loads on the
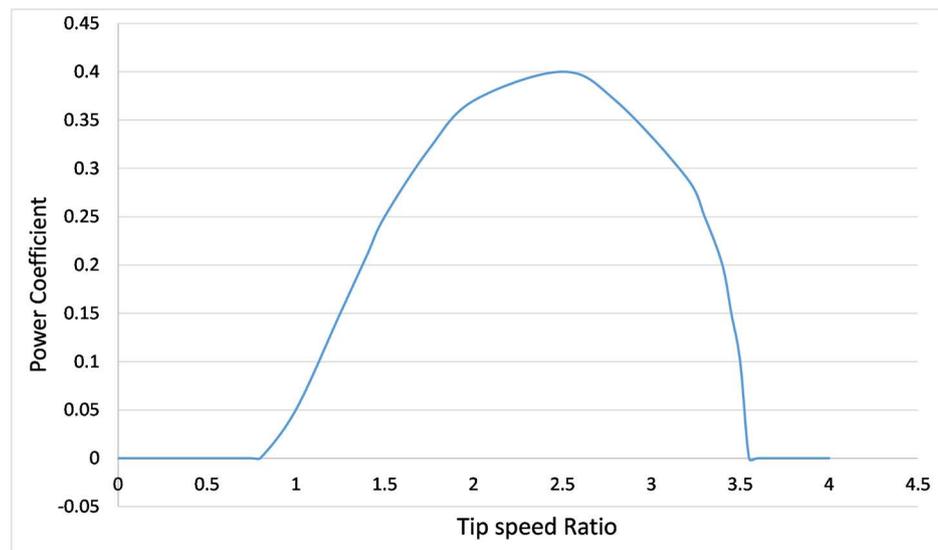

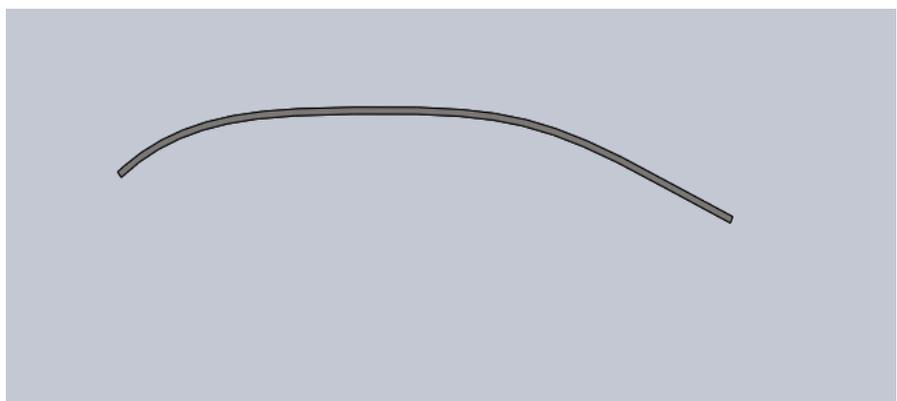**Figure 1.** Variation of power coefficient with tip speed ratio [6].

Figure 2. 2D Circular arc blade profile.

blades: gravitational, centrifugal and hydrodynamic forces were used for structural analysis. The result for the maximum and minimum von-Mises stresses, factor of safety and total deformation (displacements) over the complete blade geometry for different blade thickness are presented in **Table 2**.

The blades have high Von-Mises stresses at the rear part near the hub and the deformation is high at the tip of the rear part of the blades as shown in **Figure 4(a)** and **Figure 4(b)** respectively.

The stress level for blade thickness 1 (mm) exceeded the limit value and the deformation was very high with factor of safety less than 1. The stress level for blade thickness 2 (mm) was lower than the limit value but the deformation was
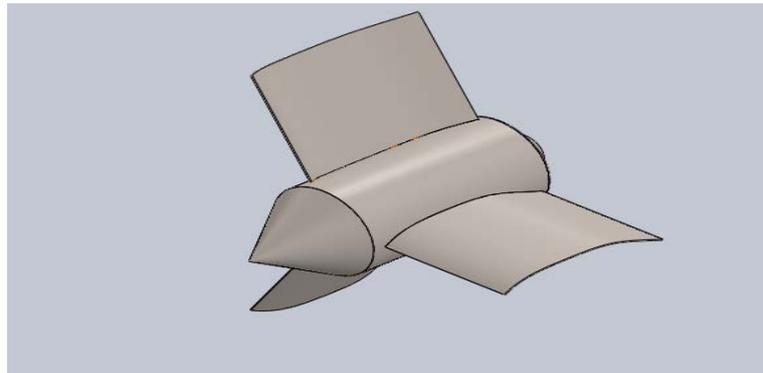

Figure 3. 3D model of the turbine.

Table 2. Structural simulation result of the blade.

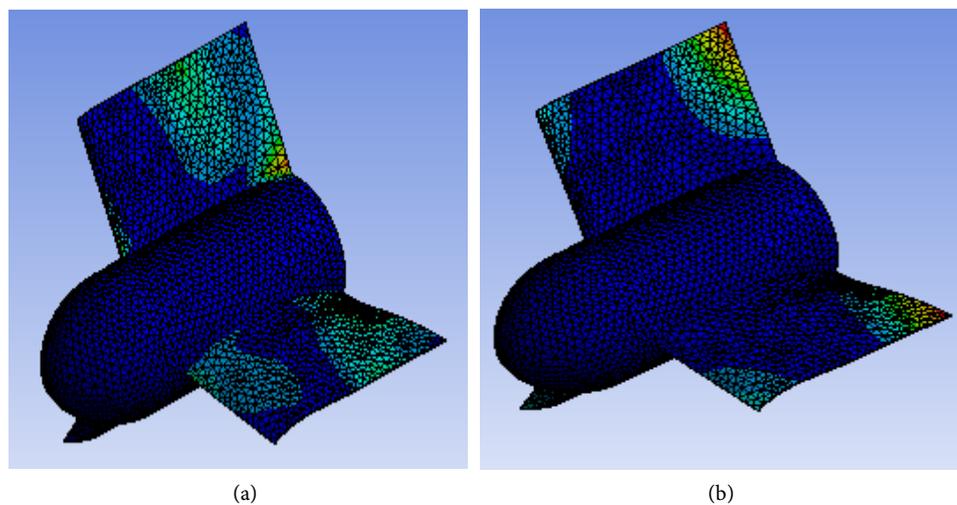| Material	Blade thickness (mm)	Von-Mises Stress (MPa)		Factor of Safety		Total deformation (mm)
		minimum	maximum	minimum	maximum	
Stainless Steel	1	4.63e - 5	437.97	0.197	15	10
Stainless Steel	2	1.13e - 5	158.58	0.544	15	2.8
Stainless Steel	3	3.73e - 7	83.96	1.5	15	0.1

| (a) | (b) |

Figure 4. (a) Von-Mise stress on the table and (b) deformation on the blade.

still high and factor of safety less than 1. On the other hand, the stress level for blade thickness 3 (mm) was very low and zero deformation with factor of safety greater than 1. Therefore, the blade thickness of 3 (mm) was adopted as the design thickness for the blade as it had high specific strength and stiffness to retain its shape under high loadings.

3. Results and Discussion

3.1. Numerical Simulation of the Circular Arc Profile

The numerical simulations were realized for a 2D configuration of the circular arc profile with 10 degrees angle of attack, using Fluent flow in ANSYS 17.0. The converged result was obtained with 26,494 nodes and 17,664 elements.

From Figure 5, the circular arc configuration experiences little flow separation at the tip end of the blade and vortex is encountered in the wake region not on the blade. This eliminates losses of lift force as the effects of adverse pressure gradient on the blade are minimal because of little flow separation on the blade. Figure 6 shows the pressure distribution on the blade, the hydrodynamic forces acting on the concave region of the profile are greater than the hydrodynamic force acting on the convex region, this is confirmed in Figure 7 by static pressure distribution on the blade. This result shows the blade experiences more lift which results in an increased torque on the rotor.

3.2. Comparison of Experimental Results with Numerical Simulation

The prototype turbine was tested in the Kabalenga River, Nchelenge district, Luapula
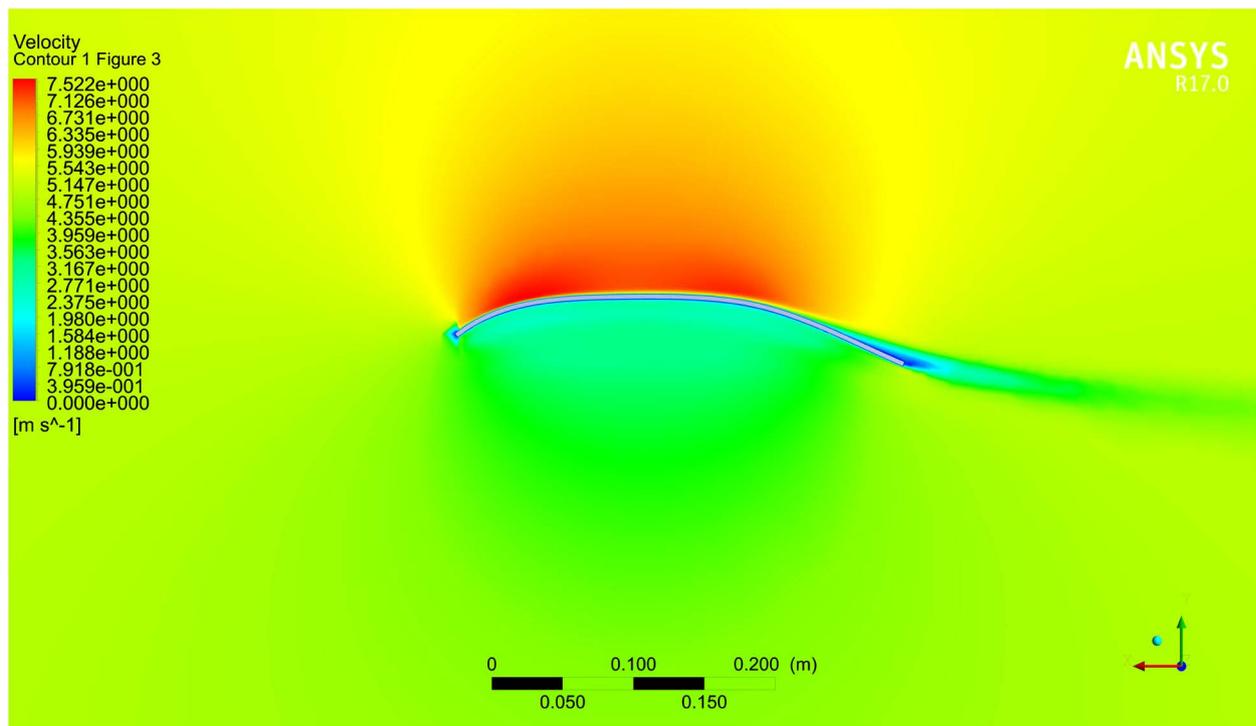

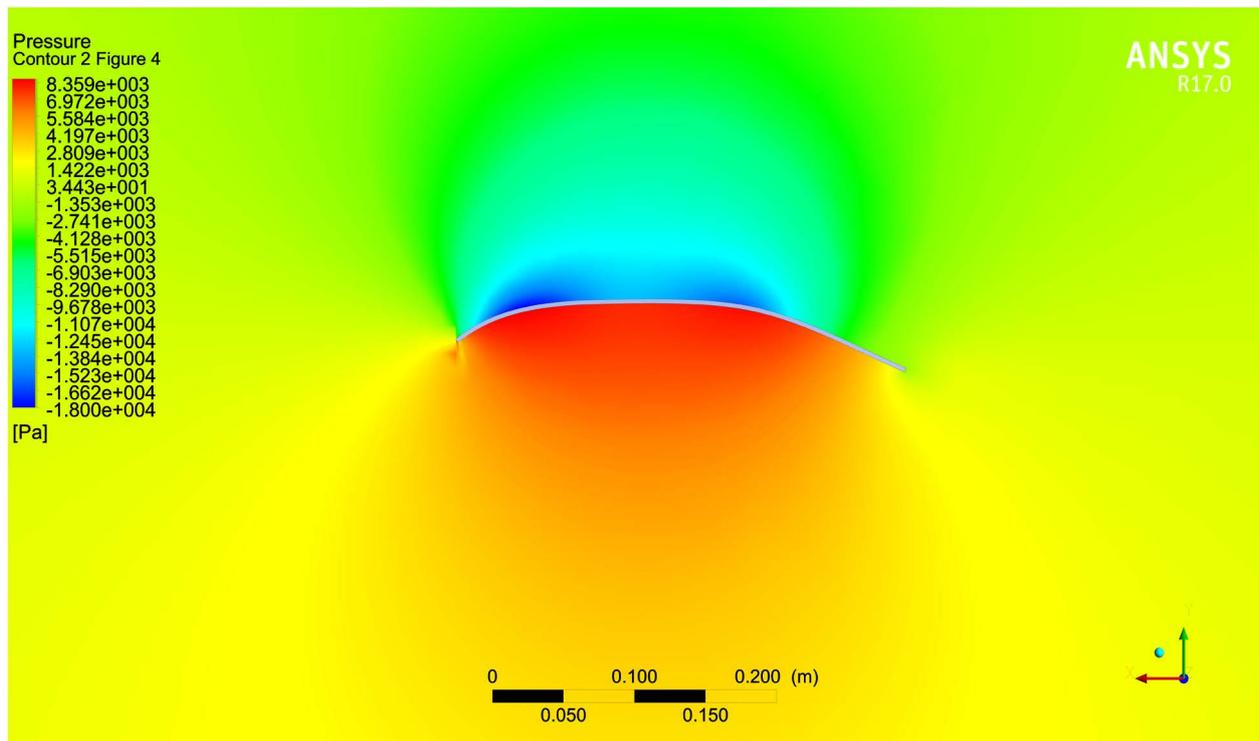**Figure 5.** Distribution of velocity for a circular arc profile.

Figure 6. Distribution of pressure for circular arc profile.
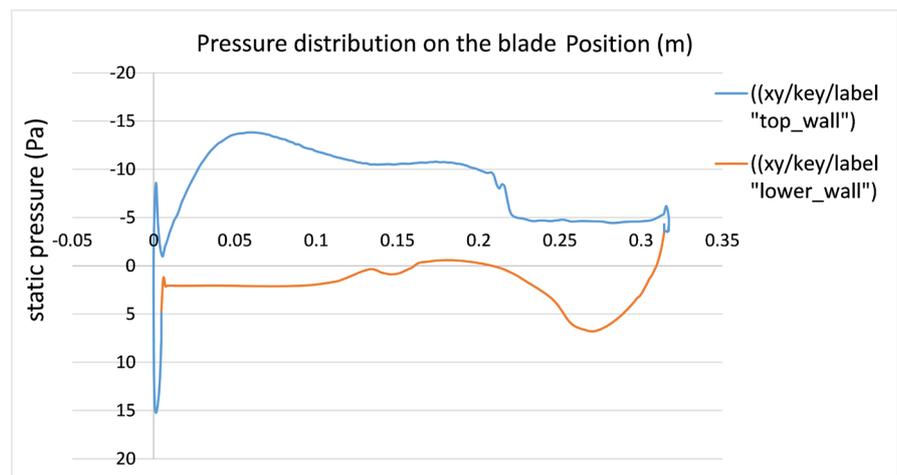

Figure 7. Static pressure distribution on the lower and top part of the blade.

Province at the water velocity of 0.596 m/s. The measured angular speed on the shaft was 26 rpm and measured torque was 9.81 Nm translating into 26.997 W power. The numerical simulation of a 3D circular arc blade horizontal axis hydrokinetic turbine model was realized using CFX in ANSYS 17.0. The converged result was obtained at 96,922 nodes and 492,961 elements. Using same flow velocity of 0.596 m/s and turbine angular speed of 26 rpm, the torque on the rotor from the software was 12.348 Nm and the power output was 33.98 W. **Figure 8** shows the variation of torque with flow velocity and **Figure 9** shows the variation of power extracted from water with flow velocity. The simulation results
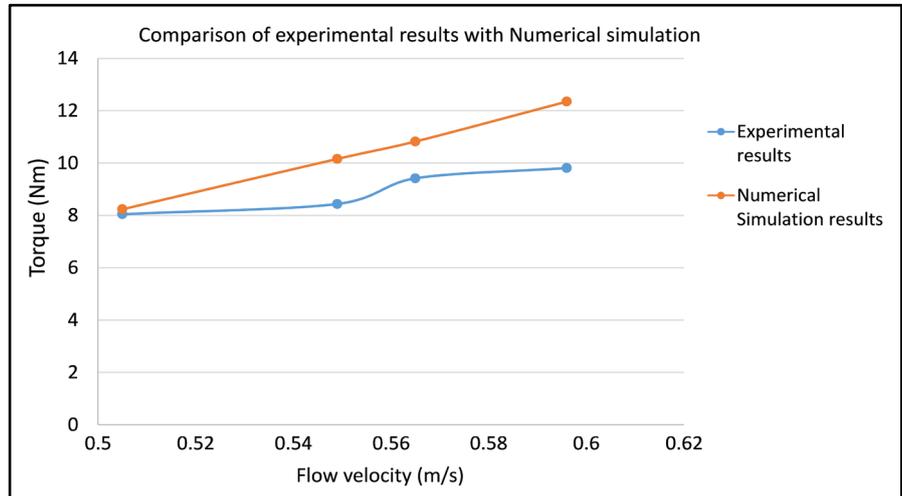
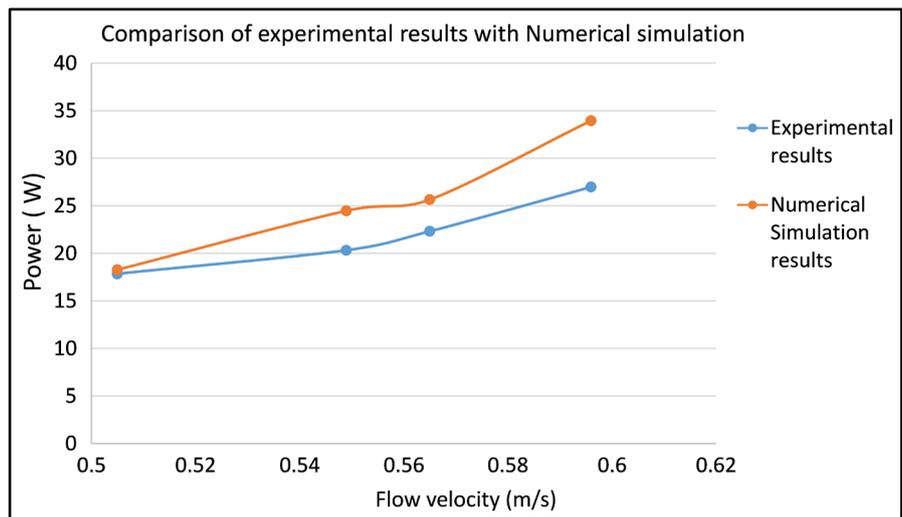**Figure 8.** Variation of Torque with flow velocity.

Figure 9. Variation extracted Power with flow velocity.

shows high values of result than experimental results, this could be attributed to the fact the prototypes turbine experienced some friction in the bearings and power transmitting belt hence lower values of the results.

4. Conclusion

In conclusion, the work describes the approach to be used in the design of cheap and easy to maintain hydrokinetic turbine for rural areas application. From the numerical simulation and practical result, it is shown that even at low water velocity (*i.e.* 0.5 m/s), the turbine is capable of generating meaningful power due to blade configuration which generates more lift force and less drag force whereby increasing rotor torque. It was observed that the significant power extraction from the River by the turbine can be achieved by high river flow velocity in the range of 1 m/s and above. For deeper rivers, a bigger diameter turbine of same blade profile can be used to extract more hydro-power.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

ZESCO—Zambia Electricity Supply Company

IEA—International Energy Agency

REA—Rural Electrification Authority

NACA—National Advisory Committee for Aeronautics

FEM—Finite Element Method

λ—Tip Speed Ratio

η—Drive Chain Efficiency

C_p—Turbine Power Coefficient