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Optimization of the Operational Conditions for Cross Flow Turbine Developed for Power Generation

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Abstract

In a bid to optimize the performance of a Cross Flow Turbine designed and fabricated by Oyebode (2014), the performance evaluation of the turbine at various conditions was carried out using a portion of the overflow from the University of Ilorin (UNILORIN) dam. The Dam has a net head of 4 m, flow rate of 0.017m^3 and hence theoretical hydropower energy of 668W. The turbine was tested and the optimized value of operating conditions namely; angle of inclination of the water jet (15^o above tangent, tangential and 15^o below tangent), height of water jet to impact point (200mm, 250mm and 300mm) and length of the water jet to impact point (50mm, 100mm and 150mm) were pre-set at their various levels while testing the Turbine. The measured outputs were Turbine Speed, Turbine Torque, Alternator Speed as well as the output voltage. The optimum values of the process output or measured parameters were determined statistically using a 3^3X2 factorial experiment in three replicates. An optimum turbine speed of 330.09 rpm was achieved by pre-setting 250mm height to impact point, 100mm length to impact point and the water jet 15º below tangent. Same combination also yielded an optimum turbine torque of 39.07kNm. During loading (i.e. when the alternator becomes connected to the turbine), an optimum Turbine Speed of 197.66rpm was achieved by pre-setting 250mm height to impact point, 100mm length to impact point and the water jet 15º below tangent. Same combination also yielded an optimum Turbine Torque of 25.02kNm, optimum Alternator speed of 879.24rpm and an optimum output voltage of 4.05V. The results therefore show that the turbine must be set at these operational conditions for it to perform optimally.

Key words: Micro hydropower, Cross Flow turbine, Power generation, Dam overflow

1. Introduction

Hydropower plants utilizes the kinetic energy developed by moving water from sources such as the rivers, ocean, and waterfalls to turn vane-like blades in a turbine which in turn turns a shaft connected to a generator, thereby converting the kinetic energy of moving water to mechanical energy. The mechanical energy developed can be used directly for powering machine or can be used to run electricity generators which have a powerful electromagnet (a rotor) which is turned inside a coil of copper bars (a starter). This produces an electromotive force or the process of exciting electrons to jump from atom to atom. When electrons flow along a wire or other conductor, jumping from atom to atom, they create an electric current or a flow of electricity.

2. Overview of Hydropower Generation in Nigeria

The first hydropower supply station in Nigeria is at Kainji on the river Niger where the installed capacity is 836MW with provisions for expansion to 1156 MW. A second hydropower station on the Niger is at Jebba with an installed capacity of 540 MW. An estimate by Aliyu and Elegba, (1990) for rivers Kaduna, Benue and Cross River (at Shiroro, Makurdi and Ikom, respectively) put their total capacity at about 4,650MW. Estimates for the rivers on the Mambila Plateau are put at 2,330MW. The foregoing assessment is for large hydro schemes which have predominantly been the class of schemes in use prior to the oil crisis of 1973. Since that time, however, many developed and developing countries have opted for small scale hydropower with appreciable savings made over the otherwise alternative to crude oil. It should be noted that hydropower plants that supply electrical energy between the range of 15kW to 15MW are mini-hydro while those supplying below 15kW are normally referred to as micro-hydro plants (Sambo, 1997). Indeed, small scale (both micro and mini) hydropower systems possess so many advantages over large hydro systems, which includes ease of setting up, low maintenance requirement, less skilled operators required and the problems of topography is minimal. In effect, small hydropower systems can be set up in all parts of the country so that the potential energy in the large network of rivers can be tapped and converted to electrical energy. In this way the nation's rural electrification projects can be greatly enhanced. Hydropower has been regarded as the ideal fuel for electricity generation because, unlike the non-renewable fuels used to generate electricity, it is almost free, there are no waste products, and hydropower does not pollute the water or the air. However, it is criticized because it does change the environment by affecting natural habitats and large hydropower schemes have been seen as a weapon of mass destruction in case of failure or attack during war (EIA, 2004). Furthermore, the estimated long-term power demand of Nigeria was 25GW for the year 2010 to sustain industrial growth (Okpanefe and Owolabi, 2001). The Power Holding Company of Nigeria (PHCN, as it was then called) has an installed capacity of only 6GW, out of which less than 2.5GW is the actual available output. Of this, thermal plants provide 61%, while hydropower generation is about 31% (Olivia, 2008). This shows a gross underdevelopment of the hydropower potetials of Nigeria. Developing micro hydropower could therefore be a solution to the inadequate power supply from the national grid especially to rural areas. It can as well be a key driver in rural development programs

2.1 Cross Flow Turbine

This type of turbine has a drum-shaped runner consisting of two parallel discs connected together near their rims by a series of curved blades (Mokmore and Merryfield, 1949). A Cross flow turbine always has its runner shaft horizontal (unlike turbine which can have either horizontal or vertical shaft orientation). They will work on net heads from just 1.75m all of the way to 200m, though there are more appropriate turbine choices for sites with heads above 40m. They will work on average annual flows as low as 40l/s up to $5m^3/s$, though on the higher flow rates there may be other better turbine types to consider.

The water flows over and under the inlet guide-vane which directs flow to ensure that the water hits the rotor at the correct angle for maximum efficiency. The water then flows over the upper rotor blades, producing a torque on the rotor, then through the centre of the rotor and back across the low rotor blades producing more torque on the rotor. Most of the power is extracted by the upper blades (roughly 75%) and the remaining 25% by the lower blades (Robert and Robert, 2002). Obviously, the rotor is rotating, so what are the upper blades one moment will be the lower blades the next.

2.2 Advantages of Cross Flow Turbine

The peak efficiency of a cross-flow turbine is somewhat less than a Kaplan, Francis or Pelton turbine. However, the cross-flow turbine has a flat efficiency curve under varying load. With a split runner and turbine chamber, the turbine maintains its efficiency while the flow and load vary from 1/6 to the maximum (Craig and Cox, 1971). Since it has a low price, and good regulation, cross-flow turbines are mostly used in mini and micro hydropower units of less than two thousand kW and with heads less than 200m. Particularly with small run-of-the-river plants, the flat efficiency curve yields better annual performance than other turbine systems, as small rivers' water is usually lower in some months. The efficiency of a turbine determines whether electricity is produced during the periods when rivers have low flows. If the turbines used have high peak efficiencies, but behave poorly at partial load, less annual performance is obtained than with turbines that have a flat efficiency curve (Craig and Cox, 1971). Due to its excellent behavior with partial loads, the cross-flow turbine is well-suited to unattended electricity production. Its simple construction makes it easier to maintain than other turbine types; only two bearings must be maintained, and there are only three rotating elements. The mechanical system is simple, so repairs can be performed by local mechanics. Another advantage is that it can often clean itself. As the water leaves the runner, leaves, grass etc. will not remain in the runner, preventing losses. Therefore, although the turbine's efficiency is somewhat lower, it is more reliable than other types. No runner cleaning is normally necessary, e.g. by flow inversion or variations of the speed. Other turbine types are clogged more easily, and consequently face power losses despite higher nominal efficiencies (Mokmore and Merryfield, 1949).

In spite of the numerous advantages possessed by the Crossflow turbine, the conditions under which it operates have not been adequately optimized (Oyebode, 2014). This is because there are still so many unanswered questions regarding design and optimization especially for the flow field characteristics. Therefore, an optimization studies that evaluate and establishes optimum operating conditions for the flow field is therefore desirable. This was hence the objective of this research.

3. Materials and Methods

3.1 *Description of the Crossflow Turbine*

The Developed Hydropower machine is made up of the Crossflow Turbine, Nozzle, Alternator, Pulley, Bearing, Shaft, Adjuster, Cover, Frame, etc. as shown in Figure 1. Figure 2 is the pictorial view of the Crossflow Turbine used.

3.2 *The Crossflow Turbine*

Table 1 is a summary of the specifications of the Crossflow turbine, head of water (h), discharge (q) and the theoretically available hydropower from the portion of the dam overflow used for the experiment.

Table 1: Summary Table for the Crossflow Drum

S/N	PARAMETER	DIMENSION
1.	Hydraulic Head (H_n)	4.0m
2.	Flow Rate (q)	1.7 X 10^{-2} m^3s^{-1}
3.	Available Power	667 Watts
4.	Rotational Speed (rpm)	1500 rpm
5.	Rotor Diameter (d_1)	300mm
6.	Position of Water Jet	16 degrees
7.	Position of Blades	30 degrees
8.	Inner Diameter (d_2)	198mm
9.	Radius of Blade (r_b)	50mm
10.	Spacing of Blabe (t)	28mm

3.3 *Nozzle*

The nozzle is made up of a galvanized steel pipe with an inlet radius of 100mm and an outlet radius of 50mm. It receives the flowing water and discharges it at a higher velocity to the turbine. It has been designed in a way that allows it to be raised upward and downward, it could also be moved forwards and backwards towards the Turbine blades, it can as well be inclined at varying inclinations.

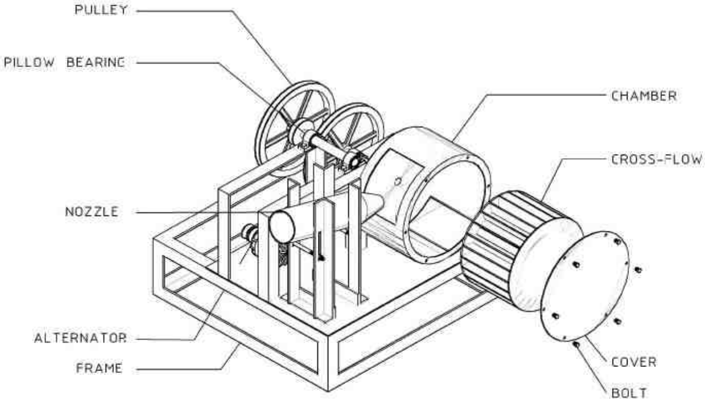

Figure 1:- Description of the Machine

Figure 2:- Pictorial View of the Cross Flow Turbine

3.4 *Alternator*

The used alternator was a second hand 12V diesel engine alternator. A survey of similar brands revealed that the alternators are rated 650 watts and run between 1000 and 1500 rpm.

3.5 *Geography and Local Geology of the Study Area*

University of Ilorin (UNILORIN) dam site is located within the university campus which lies entirely within the basement rocks in the Western part of Central Nigeria bounded by longitudes 4° 39′ 51.6″ - 4° 40′ 02.50″ E and latitudes 8° 27′ 54.2″ - 8° 28′ 4.7″ N. It falls within the eastern part of Ilorin. The study zone is a semi-arid region of Nigeria with vegetation mainly of the guinea savannah type with shrubs and undergrowth. Rugged troughs and crests due to erosions characterize the topography of the area (Taiwo, 1998). The main river within the campus is river Oyun which flows from southeast-northwest direction (Sule, *et al., 2011).*

3.6 *The University of Ilorin (Unilorin) Dam*

Figure 3 shows the pictorial view of the University of Ilorin (UNILORIN) dam. it was commissioned in 2007 primarily for water supply; it is located on the Oyun River. The Dam is a zoned earth fill embankment with an ogee-shaped concrete spillway. The intake for water supply and the low lift pumping station are located on the wing wall.

Figure 3: Pictorial View of Unilorin Dam
Source: Akoshile, and Olaoye, (2008)

3.7 *Water Resources of the Dam*

To decide the hydropower potential of any flow, it is important to begin with an evaluation of the available water resource. The energy potential of the scheme is directly proportional to the flow and head. To fairly select the most appropriate hydraulic equipment and estimate the dam's hydropower potential, the water resource analysis took into consideration the water to meet the primary responsibility of the Dam. Considering this, only the water from the spill way was available for use

3.8 *Hydraulic Head (h).*

In hydroelectric projects, calculations are based on the available hydraulic head. This is a measurement of the difference in elevation between the water source and the turbine. For this project, the head was measured (using a change in height method) to be 4m.

3.9 *Flow Rate (q).*

A portion of the overflow was channeled into a pipe. To measure the amount of water available through the pipe, (known as the flow rate), the water supply was opened, and the amount that flowed out in 10 seconds was collected in a large bucket. Once the experimental time had elapsed, the content of the bucket was measured by pouring it into a measuring cup. The following is a summary of the calculations;

170 litters was collected in 10 seconds
i.e., 17l/s

$$q = 1.7 \times 10^{-2}\ m^3s^{-1}$$

3.10 *Available Hydro Power from Unilorin Dam.*

Power (kW) = [Flow Rate] x [Hydraulic Head] x [Gravity] x [Density of Water] x [Efficiency] x [1/1000]

Or

$P (kW) = q \times h \times g \times \rho \times \eta \times [1/1000]$

As this calculation is just designed to give the upper limit, an efficiency of 100% was assumed.

$P (kW) = 1.7 \times 10^{-2} \times 4 \times 9.81 \times 1000 \times [1/1000]$

= 0.66708 kW Or 667.08Watts

3.11 *Experimental Factors*

The operating conditions manipulated were angle of inclination of the water jet (15° above tangent, tangential, and 15° below tangent), Height of the water jet to Impact Point (200mm, 250mm and 300mm), and Length of the water jet to impact point (50mm, 100mm and 150mm). The effect of these process parameters on the various outputs were investigated under two different conditions (off-load and on-load). The off-load implies that the turbine was left to run without attaching the alternator while the on-load condition implies that the alternator had been connected to the Turbine by means of a belt and pulley system. The pulley system was designed to deliver the rotational speed at the rate of 1:6.

The performance of the turbine was evaluated using a 3^3X2 (three factors and three levels under two conditions) factorial experimental design. Table 3 shows the factorial experimental design layout used.

Table 2. Design Layout for Treatment Combination

				HORIZONTAL								
				H1			H2			H3		
				VERTICAL								
				V1	V2	V3	V1	V2	V3	V1	V2	V3
CONDITION	C1	INCLINATION	I1	C1I1V1H1	C1I1V2H1	C1I1V3H1	C1I1V1H2	C1I1V2H2	C1I1V3H2	C1I1V1H3	C1I1V2H3	C1I1V3H3
			I2	C1I2V1H1	C1I2V2H1	C1I2V3H1	C1I2V1H2	C1I2V2H2	C1I2V3H2	C1I2V1H3	C1I2V2H3	C1I2V3H3
			I3	C1I3V1H1	C1I3V2H1	C1I3V3H1	C1I3V1H2	C1I3V2H2	C1I3V3H2	C1I3V1H3	C1I3V2H3	C1I3V3H3
	C2		I1	C2I1V1H1	C2I1V2H1	C2I1V3H1	C2I1V1H2	C2I1V2H2	C2I1V3H2	C2I1V1H3	C2I1V2H3	C2I1V3H3
			I2	C2I2V1H1	C2I2V2H1	C2I2V3H1	C2I2V1H2	C2I2V2H2	C2I2V3H2	C2I2V1H3	C2I2V2H3	C2I2V3H3
			I3	C2I3V1H1	C2I3V2H1	C2I3V3H1	C2I3V1H2	C2I3V2H2	C2I3V3H2	C2I3V1H3	C2I3V2H3	C2I3V3H3

KEY

H - Height of water jet to impact point
V - Length of water jet to impact point
I - Inclination of water jet to impact point
C - Condition of the Turbine (1 – Off load, 2 – On load)

3.12 *Measured Parameters*

i) Speed: -The speed was measured using a tachometer. The nob of the tachometer was placed at the punched center of the shaft and the readings were recorded. The Tachometer used was a contact type and it was manufactured by Fisons. The model is TAF – 420 – K and it has a capacity of 100,000 rpm.

ii) Output Voltage: -The output voltage was measured using a D.C. Multimeter. It was manufactured by Fison. The model is DT9205M and it has a capacity of 1000V

iii) Torque: - *The turbine torque was measured using a hand-held Shimpo FG-7000T-3 Digital Torque Meter*

4. Results and Discussion

4.1 *Descriptive Statistics*

Table 3 shows the summary statistics of the data collected during the Experiment. It can be inferred from the table that the mean values of Turbine speed vary depending on the operation parameters being employed. Variations in Turbines speed also occurred along the levels of operation parameter. Similar pattern was observed for all other output namely; Turbine Torque, Alternator Speed and Output voltage. These may suggest that operations parameter manipulated does not have same effect on the output/responses.

Table 3: Descriptive Statistics of Speed of Turbine and Torque using the Various Operation Parameter

Process Parameter	Level	Turbine Speed		Turbine Torque		Alternator Speed		Output Voltage	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Condition	Off Load	251.20	36.70	29.74	4.34				
	On Load	150.63	22.54	19.08	2.85				
Inclination (I)	15° above	188.30	55.34	22.88	6.08	632.00	93.82	2.92	0.43
	Tangential	198.43	56.58	24.11	6.19	671.70	83.79	3.10	0.39
	15° below	216.02	62.15	26.24	6.81	724.19	101.73	3.34	0.47
	250mm	342.20	73.91	30.36	5.60	1275.26	156.81	5.89	0.72
	300mm	406.41	76.62	36.05	5.47	1509.70	100.11	6.97	0.46
Height to Impact Point (H)	200mm	190.81	54.39	23.18	5.94	642.63	81.32	2.97	0.37
	250mm	222.67	61.92	27.05	6.74	746.44	97.16	3.44	0.45
	300mm	189.26	54.88	22.99	6.01	638.81	82.55	2.95	0.38
	75mm	397.43	77.45	35.26	5.62	1484.96	119.06	6.85	0.55
	125mm	351.22	76.90	31.16	5.88	1307.59	171.30	6.03	0.79
Length to Impact Point (V)	50mm	201.04	58.54	24.43	6.43	684.00	97.31	3.16	0.45
	100mm	224.61	59.54	27.28	6.39	751.78	60.73	3.47	0.28
	150mm	177.09	49.06	21.51	5.32	592.11	64.18	2.73	0.30

4.2 Effect of Operation Parameters on Turbine Speed and Turbine Torque for Off-load Condition

4.2.1. *Turbine Speed*

Table 4 shows the effect of angle of inclination, height to impact point and length to impact point pre-set at various levels on Turbine speed under Off-load condition. The results show that the pre-set levels of the three operating parameters was statistically significant at 5% level. The hypothesis of equal Turbine Speed irrespective of the operation parameters was therefore rejected. This means that variations observed in Turbine Speed as recorded in Table 2 were actually due to effect of the operation parameters and not by chance occurrence.

To determine the differences in the contributions of angle of inclination, height to impact point and length to impact point on mean effect of Turbine Speed, New Duncan's Multiple Range Test (DMRT) was conducted (Table 5). The result of the comparison of Turbine Speed among the three levels of angle of inclination (15º above, tangential and 15 º below) shows that the observed means of Turbine Speed are significantly different from one level to the other. The highest Turbine speed of 270.26rpm was observed at 15º below tangent level and this value was significantly higher than the other two preset levels of inclination (tangential and 15º above tangent). The mean speed of 247.70rpm observed at tangential level was also statistically higher than the mean speed of 235.63rpm observed at 15º above tangent.

Table 5 also revealed that highest Turbine speed was at 250mm height impact point. The mean Turbine speeds of 238.63rpm and 237.15rpm were observed at 200mm and 300mm height to impact points respectively. These two levels of height to impact point recorded the same speed on the average. A higher Turbine speed of 466.74rpm was observed at 100mm Length to Impact Point. This value was significantly higher than Turbine speed observed at 150mm and 50mm respectively.

Table 4: Effect of Process Parameter on Turbine Speed in Off-load Condition

Source	Sum of Squares	Df	Mean Square	F	Sig
A	16683.73	2	8341.86	501.63	0.001*
B	28723.06	2	14361.53	863.61	0.001*
C	47053.14	2	23526.57	1414.74	0.001*
A * B	1568.49	4	392.12	23.58	0.001*
A * C	5859.75	4	1464.94	88.09	0.001*
B* C	561.53	4	140.38	8.44	0.001*
A*B*C	6379.14	8	797.39	47.95	0.001*
Error	898.00	54	16.63		
Total	107726.84	80			

*A=Inclination, B=Height to Impact Point, C=Length to Impact Point, *=Significant @ 5%*

Table 5: Comparing the mean values of Turbine Speed using Duncan Multiple Range Test

Factor	Level	Turbine Speed
Inclination	15º above	235.63a
	Tangential	247.70b
	15º below	270.26c
Height to Impact Point	200mm	238.63a
	250mm	277.81b
	300mm	237.15a
Length to Impact Point	50mm	251.07a
	100mm	280.78b
	150mm	221.74c

Means with the same alphabet are not significantly different from each other

4.2.2. *Turbine Torque*

The result of the effect of operation conditions on Turbine Torque is presented on Table 6. It was observed that all the process conditions and their interactions had significant effect on Turbine Torque without load application at 5% level of significance. This implies that each operation conditions independently influenced Turbine Torque and also had combined effect on the Turbine Torque. It can therefore be concluded from the foregoing that at least one treatment effect is significantly different from the others. Tables 7 shows the comparisons between the different levels of the process condition using the New Duncan Multiple Range Test (DMRT). In comparing the means of Turbine Torque at the three levels of angle of inclination considered in the study, a torque of 27.89kNm was achieved at 15º above tangent while the highest Turbine Torque of 32.00kNm was observed at 15º below tangent. At 250mm height to impact point, a Turbine Torque of 32.88kNm was observed which is statistically higher than Turbine Torque observed at 200mm and 300mm respectively. Similarly, a significantly higher mean Turbine Torque of 33.23kNm was observed at 100mm length to impact point while a lower Turbine Torque of 29.73kNm and 26.73kNm was observed at 50mm and 150mm respectively.

Table 6: Effect of Process Parameter on Turbine Torque in Off-load Condition

Type of Machine	Source	Sum of Squares	Df	Mean Square	F	Sig
Cross Flow Turbine	A	234.40	2	117.20	503.08	0.001*
	B	401.19	2	200.59	861.05	0.001*
	C	659.40	2	329.70	1415.25	0.001*
	A * B	22.19	4	5.55	23.81	0.001*
	A * C	82.45	4	20.61	88.48	0.001*
	B* C	7.86	4	1.96	8.43	0.001*
	A*B*C	89.50	8	11.19	48.02	0.001*
	Error	12.58	54	0.23		
	Total	1509.57	80			

*A=Inclination, B=Height to Impact Point, C=Length to Impact Point, *=Significant @ 5%*

Table 7: Comparing the mean values of Turbine Torque using Duncan Multiple Range Test

Turbine Type	Process Parameter	Level	Turbine Torque
Cross Flow Turbine	Inclination	15º above	27.89a
		Tangential	29.32b
		15º below	32.00c
	Height to Impact	200mm	28.25a
		250mm	32.88b
		300mm	28.07a
	Length to Impact	50mm	29.73a
		100mm	33.23b
		150mm	26.24c

Means with the same alphabet are not significantly different from each other

4.3 Effect of Operating Parameters on Process Output for On-load Condition

4.3.1. *Turbine Speed*

Table 8 shows the effect of operating parameters on the turbine speed at on-load condition, it was observed that angle of inclination, height to impact point and length to impact point had significant effect on Turbine Speed when the Turbine is on load at 5% level of significance. The interactions between these process parameters also had significant effect on Turbine Speed at 5% level of significance. This implies that at least one level of the operating conditions manipulated is significantly different from the others. Table 9 compares the mean of Turbine speed along the levels of angle of inclination, height to impact point and length to impact point the Crossflow Turbine, 15º below tangent angle of inclination had higher mean value of Turbine speed (161.78rpm) followed by angle at tangential (149.15rpm) and 15º above tangent (140.96rpm). At 250mm heights to impact point, a significantly higher Turbine speed (167rpm) was observed. A relatively similar mean Turbine speed of 143.00rpm and 141.37rpm respectively was observed at 200mm and 300mm height to impact point. Similarly, 100mm length to impact point recorded the most significantly higher mean Turbine speed (168.44rpm) for Cross Flow Turbine. The mean Turbine speed of 151.00rpm observed at 50mm length to impact point is significantly higher than the mean Turbine speed of 132.44rpm observed at 150mm

Table 8: Effect of Process Parameter on Turbine Speed in On-load Condition

Type	Source	Sum of Squares	Df	Mean Square	F	Sig.
Cross Flow Turbine	A	5937.85	2	2968.93	298.00	0.001*
	B	11587.85	2	5793.93	581.55	0.001*
	C	17501.56	2	8750.78	878.33	0.001*
	A * B	649.19	4	162.30	16.29	0.001*
	A * C	2438.37	4	609.59	61.19	0.001*
	B* C	425.93	4	106.48	10.69	0.001*
	A*B*C	1578.15	8	197.27	19.80	0.001*
	Error	538.00	54	9.96		
	Total	40656.89	80			

*A=Inclination, B=Height to Impact Point, C=Length to Impact Point, *=Significant @ 5%*

Table 9: Comparing the mean values of Turbine Speed using Duncan Multiple Range Test

Machine Type	Factor	Level	Turbine Speed
Cross Flow Turbine	Inclination	15° above	140.96a
		Tangential	149.15b
		15° below	161.78c
	Height to Impact	200mm	143.00a
		250mm	167.52b
		300mm	141.37a
	Length to Impact	50mm	151.00a
		100mm	168.44b
		150mm	132.44c

Means with the same alphabet are not significantly different from each other

4.3.2. *Turbine Torque*

Table 10 shows the effect of angle of inclination, height to impact point and length to impact point preset at various levels, on Turbine Torque at On-load condition. The results show that the preset levels of the three process parameters was statistically significant at 5% level. The hypothesis of equal Turbine Torque irrespective of the process parameters was therefore rejected. This means that variances earlier observed in Turbine Torque in Table 3 above were actually due to effect of the operating parameters namely; angle of inclination, height to impact point and length to impact point.

Table 11 shows the comparisons between the different levels of angle of inclination, height to impact point and length to impact point using the New Duncan Multiple Range Test (DMRT) for the crossflow Turbine, the highest Turbine Torque of 20.49kNm was observed at 15° below tangent level and this value was significantly higher than the other two preset levels of inclination (tangential and 15° above tangent). The mean Torque of 18.89kNm observed at tangential level was also statistically higher than the mean Torque of 17.86kNm observed at 15° above tangent.

It could also be seen from Table 11 that a higher Turbine Torque of 21.21kNm was observed at 250mm height to impact point. The mean Turbine Torques of 18.11kNm and 17.91kNm were observed at 200mm and 300mm height to impact points respectively. These two levels of height to impact point recorded the same Torque on the average. Length to impact point at 100mm recorded significantly higher mean value of Turbine Torque (21.33kNm) relative to 50mm (19.13kNm) and 150mm (16.78kNm) height to impact point.

Table 10: Effect of Process Parameter on Turbine Torque in On-load Condition

Type	Source	Sum of Squares	Df	Mean Square	F	Sig.
Cross Flow Turbine	A	94.50	2	47.25	300.17	0.001*
	B	185.29	2	92.64	588.56	0.001*
	C	280.26	2	140.13	890.22	0.001*
	A * B	10.38	4	2.59	16.48	0.001*
	A * C	38.24	4	9.56	60.74	0.001*
	B* C	6.88	4	1.72	10.92	0.001*
	A*B*C	25.08	8	3.14	19.92	0.001*
	Error	8.50	54	0.16		
	Total	649.11	80			

*A=Inclination, B=Height to Impact Point, C=Length to Impact Point, *=Significant @ 5%*

Table 11: Comparing the mean values of Turbine Torque using Duncan Multiple Range Test

Machine Type	Factor	Level	Turbine Torque
Cross Flow Turbine	Inclination	15° above	17.86a
		Tangential	18.89b
		15° below	20.49c
	Height to Impact	200mm	18.11a
		250mm	21.21b
		300mm	17.91a
	Length to Impact	50mm	19.13a
		100mm	21.33b
		150mm	16.78c

Means with the same alphabet are not significantly different from each other

4.3.3 *Alternator Speed*

Table 12 shows the effect of operating parameters (angle of inclination, height to impact point and length to impact point) on Alternator Speed. The results show that variations observed in Alternator speed were significantly due to the operating parameters manipulated during the evaluation. The hypothesis of equal mean values of Alternator speed across all levels of process parameters was therefore also rejected. This means that variations observed in Alternator speed during the performance evaluation was actually due to effect of changes in the level of operating parameters manipulated or preset.

Table 13 compares the mean of Alternator speed along the three levels of angle of inclination, height to impact point and length to impact point for the Crossflow Turbine, 15° below tangent angle of inclination had higher mean value of Alternator speed (724.19 rpm) followed by angle at tangential (671.70 rpm) and 15° above tangent (632.00 rpm).

At 250 heights to impact point, a significantly higher Alternator speed (746.44rpm) was observed. A relatively same mean Alternator speed of 642.63rpm and 638.81rpm respectively was observed at 200mm and 300mm height to impact point.

Similarly, 100mm length to impact point recorded the most significantly higher mean Alternator speed (751.78rpm) for Cross Flow Alternator. The mean Alternator speed of 684.00rpm observed at 50mm length to impact point and is significantly higher than the mean Alternator speed of 592.11rpm observed at 150mm

Table 12: Effect of Process Parameter on Alternator Speed in On-load Condition

Type	Source	Sum of Squares	Df	Mean Square	F	Sig.
Cross Flow Turbine	A	115459.19	2	57729.59	414.51	0.001*
	B	201385.85	2	100692.93	723.00	0.001*
	C	346777.56	2	173388.78	1244.97	0.001*
	A * B	14701.85	4	3675.46	26.39	0.001*
	A * C	50663.70	4	12665.93	90.94	0.001*
	B* C	8850.37	4	2212.59	15.89	0.001*
	A*B*C	50601.70	8	6325.21	45.42	0.001*
	Error	7520.67	54	139.27		
	Total	115459.19	2	57729.59	414.51	

*A=Inclination, B=Height to Impact Point, C=Length to Impact Point, *=Significant @ 5%*

Table 13: Comparing the mean values of Alternator Speed using Duncan Multiple Range Test

Machine Type	Factor	Level	Alternator Speed
Cross Flow Turbine	Inclination	15° above	632.00a
		Tangential	671.70b
		15° below	724.19c
	Height to Impact	200mm	642.63a
		250mm	746.44b
		300mm	638.81a
	Length to Impact	50mm	684.00a
		100mm	751.78b
		150mm	592.11c

Means with the same alphabet are not significantly different from each other

4.3.4 *Output Voltage*

Table 14 show that various process parameters examined had significant effect on the Output voltage of the two Turbines respectively at 5% level of significance. This implies that Output Voltage of the two turbines is dependent on at least one and /or all the process parameters preset at their various levels. It can therefore be safely concluded that all process parameters manipulated do not have the same effect on the output voltage of the Turbine understudy.

Table 15 shows the comparisons between the different levels of angle of inclination, height to impact point and length to impact point using the New Duncan Multiple Range Test (DMRT). For Cross Flow Turbine Wheel, the highest output voltage of 3.41V was observed at 15° below tangent level and this value was significantly higher than the other two preset levels of inclination (tangential and 15° above tangent). The mean output voltage of 3.10V observed at tangential level was also statistically higher than the mean output voltage of 2.92V observed at 15° above tangent.

Table 15 also revealed that higher output voltage of 3.44V was observed at 250mm height to impact point. The mean output voltage of 2.97V and 2.95V were observed at 200mm and 300mm height to impact points respectively. These two levels of height to impact point recorded statistically the same output voltage on the average.

Length to impact point at 100mm recorded significantly higher mean value of output voltage (3.47V) compared to 50mm (3.16V) and 150mm (2.73V) height to impact point.

Table 14: Effect of Process Parameter on Output Voltage in On-load Condition

Type	Source	Sum of Squares	df	Mean Square	F	Sig.
Cross Flow Turbine	A	2.439	2	1.219	408.621	0.001*
	B	4.277	2	2.139	716.732	0.001*
	C	7.381	2	3.690	1236.716	0.001*
	A * B	0.315	4	0.079	26.360	0.001*
	A * C	1.079	4	0.270	90.359	0.001*
	B* C	0.186	4	0.046	15.575	0.001*
	A*B*C	1.078	8	0.135	45.138	0.001*
	Error	0.161	54	0.003		
	Total	16.91	80			

*A=Inclination, B=Height to Impact Point, C=Length to Impact Point, *=Significant @ 5%*

Table 15: Comparing the mean values of Output Voltage using Duncan Multiple Range Test

Machine Type	Factor	Level	Turbine Speed
Cross Flow Turbine	Inclination	15º above	2.917a
		Tangential	3.100b
		15º below	3.341c
	Height to Impact	200mm	2.966a
		250mm	3.444b
		300mm	2.948c
	Length to Impact	50mm	3.156a
		100mm	3.470b
		150mm	2.733c

Means with the same alphabet are not significantly different from each other

4.4. Optimization Analysis

Optimized Value of Operating Conditions and the Output

Optimization is defined as the process of finding optimum (maximum or minimum) settings of parameters (process conditions) in the model in order to obtain a predefined output or response value.

The optimized value of operating conditions namely; angle of inclination, height to impact point and length to impact point pre-set at their various levels and the optimum values of the process output or measured parameters are as presented in Table 16. The processes were optimized for both on load and off load situations. The result in Table 16 can be summarized as follows;

4.4.1. *Off-Load Condition*

An optimum Turbine Speed of 330.09rpm was achieved by presetting 250mm height to impact point, 100mm length to impact point and 15º below tangent. Same combination for also yielded an optimum Turbine Torque of 39.07kNm.

4.4.2. *On-Load Condition*

An optimum Turbine speed of 197.66rpm was achieved at preset level of 250mm height to impact point, 100mm length to impact point and at 15º below tangent. These same combinations yielded a Turbine Torque of 25.02kNm, Alternator speed of 879.24rpm and 4.05V

Table 4.21: Optimized Values of Process Parameters and Output

	Parameters	*H*	*I*	*V*	*Optimized value*	*Nature of Solution*
Off-load	*Turbine Speed*	250mm	15º below	100mm	330.09	*Maximized*
	Turbine Torque	250mm	15º below	100mm	39.07	*Maximized*
On-Load	*Turbine Speed*	250mm	15º below	100mm	197.66	*Maximized*
	Turbine Torque	250mm	15º below	100mm	25.02	*Maximized*
	Alternator Speed	250mm	15º below	100mm	879.24	*Maximized*
	Output Voltage	250mm	15º below	100mm	4.05	*Maximized*

H=height to impact point, I=angle of inclination and V=length to impact point

5. Conclusion

The operational condition for the optimal performance of a Crossflow Turbine was investigated. It was found out that same conditions; 250mm height to impact point, 100mm length to impact point and angle at 15^0 below tangential inclination gave the highest values in all measured parameters (Torque, Speed and Voltage) at both off-load and on-load condition. A direct proportionality was also observed between the alternator speed and the output voltage.

It is recommended that further research should be carried out on the optimization of nozzle sizes, number of Turbine blades, head, discharge, etc. on all the investigated parameters. Also, modelling of the system would make it easier to predict the effects of various conditions on the output.

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