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Micro-Hydro Generator using Eco-wheel system for Domestic and Industrial Building Applications

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***Abstract*—**The paper presents the preliminary part of ongoing research to design and develop a 3D sustainable renewable power station model that is feasible, competent and of high efficiency at an affordable cost. The paper is focused on the optimization of a 1D micro hydropower system. The constant supply of green power is made possible through a combination of power plants using renewable energies resources. Studies reveal that water wheels are not as efficient as turbines but could offer efficiency in excess of 80% for overshoot & undershoot water wheels, with 75% for breastshot water wheels. The technical issues that limit the water wheel efficiency have been studied and a new design is presented in this paper. The simulation to the new design is hereby presented with some experimental measurements of the efficiency and power that can be delivered with this new design.

***Keywords*—**3D sustainable power station, Hydro wheels/ turbines, efficiency.

I. Introduction

THE biggest contributor to carbon emission still remains the power generation industry as 57% of World Co2 emission worldwide comes from the burning effect of fossil fuels, 17% from the decay of biomass & deforestation all used for power generation [1]. Considering the rising rate of these figures, the implementation of renewable energy technologies to aid in reducing carbon emission is now a matter of urgency. Renewable energy technologies hence are designed to be much efficient so as to increase public and industries reliance on renewable energy technologies. Hydropower generation of which production figures is widely encouraging is predicted by the International Energy Association, UN to rise up to 6000 Terrawatt-hours by 2050 [2], hence the technology innovation of hydro wheels/turbines and their designs needs to offer a self-reliant and above the already existing 80% average efficiency currently marketed so as to help meet the set world hydro energy generation target by 2050 [3]. Various types of hydrowheels and turbines with the probability of reaching above 80% efficiency will be evaluated using secondary research data and suggestions on how this could be improved will be made. The paper will equally present the 1D system which is the design of the new micro hydro generator coupled with a Kaplan turbine as the preliminary part of the 3D sustainable renewable power station. The element will be designed using Solidworks, where a simulation will be carried to study its flow analysis amounting in an improved efficiency of the entire system. The design will offer a better wheel turbine with an improved efficiency using high fatigue strength materials chosen due to their affordability, making the entire design cost effective.

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A. Existing water wheels

There are three main categories of hydro wheels, overshoot, undershoot and breastshot equally known as Zuppinger wheel [4]. Secondary research data shows that the most efficient of the wheels is the overshoot wheel with an average output of 80% guarantying a good output power due to its distinctive geometry of cells and design inflow details and the Kaplan turbine for delivering an average output of 90% and above [5].

Considering the aim of this research to provide an above average improved efficiency at an affordable cost, an evaluation of the wheels and that of the Kaplan turbine will be conducted to analyze which will best fit the 3D renewable sustainable power station model with high efficiency and low cost. The design specifications of all the wheels and turbine herby named will be studied and an evaluation will be done considering the design likely to offer an improved efficiency

B. Overshot Water wheel

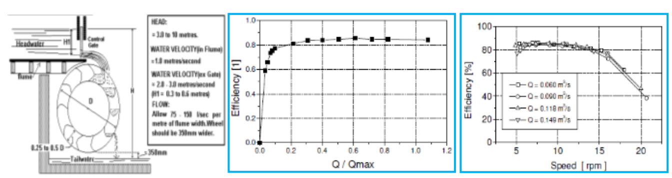

Figure 1 Efficiency Kauppert, 2003 [6] (a) Efficiency flow rate of any turbine, and (b) Efficiency against speed of overshot wheel

The principle of operation of this wheel is to capture the water in its bucket or cells where its weight allows a constant rotation of the wheel converting mechanical energy to electrical energy. The buckets or cells shape play a significant role in obtaining a good efficiency hence the design needs to be done in such a way that air can escape allowing the water jet from the inflow to enter each cell at its natural angle [7]. Capturing the water makes the wheels effective almost immediately and in order to avoid loss of water the design should consider a perpendicular shape of the buckets allowing it to be filled up to 30-50% of its total volume. The efficiency of the overshot wheel for a given application is dependent of the head difference, the diameter and flow volume with the considerations of a free or regulated inflow which impacts the head hence the speed. Figure 1 shows results of a practical Test carried out on the overshot water wheel and efficiency flow rate. Fig.1. shows a typical efficiency curve of the overshot water wheel with the efficiency reaching above 80% allowing a ratio of Q / Qmax of ≈ 0.3. The efficiency representation maintains an almost constant curve which shows that the design is efficient, and has a wide performance ratio.

C. Undershot water wheel

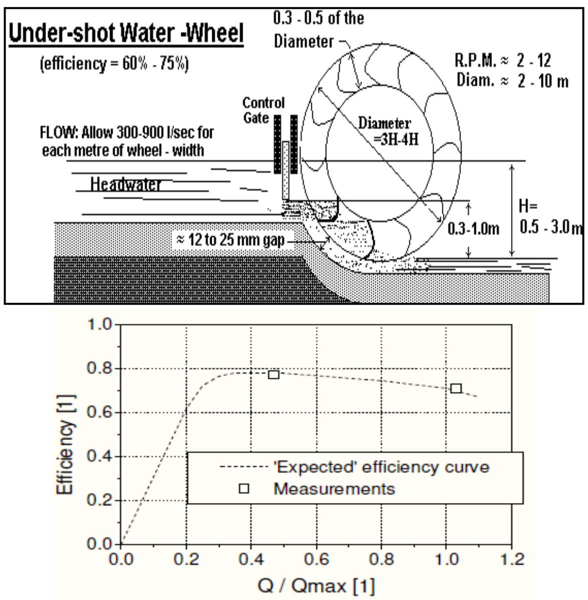

Figure 2 Schematic of the undershot (Zuppinger) water wheel [8]

The undershot water wheels operates exactly as the overshot water wheel however differs in the direction of water inflow as the Zuppinger wheel has a side elevation with a backward inclined blade and a dam type inflow. The potential energy (mgh) is used as the driving force and the size of the blades and weight offers a rotation allowing the buckets to fill rapidly. The cells are designed in such a way to accommodate about 25 to 40% of the water at entry point, which is comparably less than the overshot but less water is lost due to blade head of each cell. This is gradually reduced where water is discharged as wheel rotates with minimum loss of water. It is apparent that Geometry requirements and measurements of the space between the blades with diameter considerations should be the key to getting a good output and efficiency as shown in **Figure 2**. These design considerations should be considered before any design and manufacturing is carried out. Secondary research data reveals that most efficiency for the undershoot wheel are within the range of 60-75% making the overshot much efficient than the undershot [9].

D. Breastshot wheel

The design and topology of the breastshot water wheel makes its choice over other waterwheels very particular hence the choice is made considering location and where its application could best fit in. The design is done in such a way that the water enters the bucket at a rather steep angle which allows the bucket to be filled quicker. The cells are designed to respond to the resultant force acting in the rotating direction of the wheel making water to be reduced at a downstream of 90° angle. Similarly like the undershot the potential energy is used as the driving force so as the water pushes the paddles a rotation and period is created. The buckets or paddles are aired in order to allow air to escape during inflow and captivated back when the paddles rise above lowermost point. This simple mechanism reflects the working principle of the undershot waterwheel. Practically it was noticed that the wheel of the breastshot could only absorb 10% of its design flow rate making the rotation of the wheel very slow. The maximum efficiency obtained was estimated at approximately 79%. Considering design specifications and accurate measurements assumptions, water wheels can generate greater power even with low flow volumes without using complex control systems. The experiments carried out revealed that the power/speed curves were quite smooth, indicating that speed control of the wheels is not the focus to obtain good efficiencies but rather design speed due to good design specifications. Slow flow of water means that small gear transmissions ratios needs to be employed making energy loss within the range of 2-3% but undoubtedly haver significant effect on project cost thus ≈30% for undershot wheels and ≈45% for overshot. The experiments result carried out for the 3 wheels shows that the most efficient is the overshot water wheel with an over average 80% efficiency obtained [11].

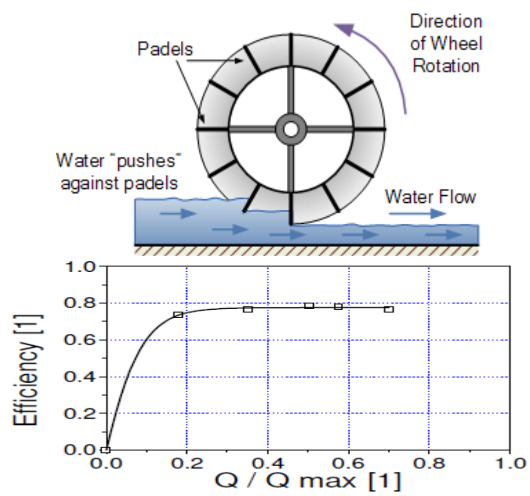

Figure 3 Schematic of the breastshot water wheel [10], (a) breastshot wheel, and (b) Principle of operation of breastshot wheel

In this paper, focus will be given to the Overshot water wheel as it reveals a better efficiency. A flow simulation of the proposed wheel using the mechanical software Solidworks will be carried out with focus on the input and output data analysis presenting the experimental measurements and results. The final section will focus on the design specification, considerations and calculation which will be thoroughly discussed and presented.

II. HYDRO WHEEL SYSTEM COMPUTER SIMULATION AND ANALYSIS

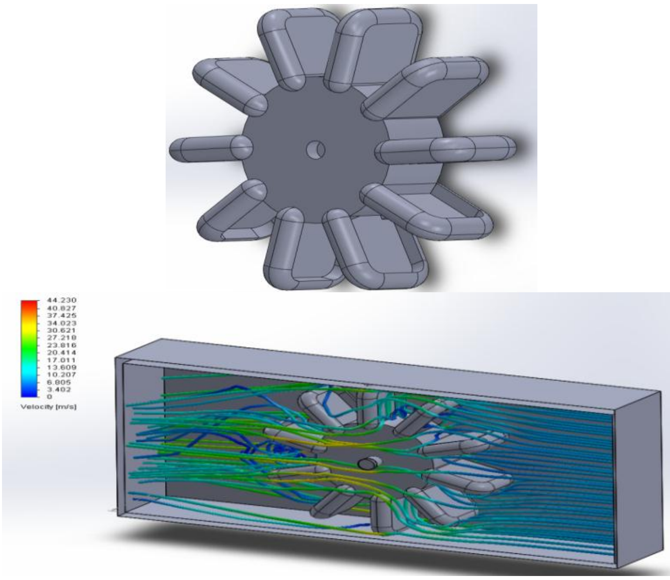

Figure 4 New eco-wheel design with flow simulation: (a) Overview of wheel, (b) Flow simulation of wheel

The design of the Eco-wheel representing the micro hydro generator was conducted by first of all considering measurements of the hydro wheel test canal and implementations of the measurements was introduce in the mechanical CAD design software Solidworks. Solidworks is a mechanical software used for design of 3D CAD (computer aided Design) able to transform ideas into product with aided tools such as 3D CAD solutions, simulations, product data management, life cycle assessment. The aim of the Eco-wheel design was to offer a wheel that will use Green products for its manufacturing and offer a better efficiency for the overshot wheel technology. As expressed earlier in this research and in reference to **Figure 2b** the estimated overshot waterwheel output efficiency is ≈ 80% on average [12]. Considering the design however, a flow simulation analysis of the wheel was then conducted using the same software where we obtained a maximum velocity of 44.23 m/s as seen in the flow simulation **Figure 8** enabling us to apply various theoretical calculations conducted in the input /output analysis section of this paper.

The efficiency was then obtained by considering the fact that the overshot waterwheel was powered by gravitational potential energy with buckets tipped out at an angle θ. It was also assumed that the reaction forces acting on the buckets are equal to the main force applied in the first instance by the water on the buckets but in different direction. In so doing the derivative of the resultant force gave a clear understanding of the role of gravity on the wheels hence we applied Newton's second law of motion to determine the force and input power. The efficiency was then obtained to be higher than the expected overshot water wheel efficiency as it was obtained to be 85.3%. Another assumption that was seriously considered was that the Eco-wheel was design with measurements of the test canal tube hence none of the water was actually lost as shown by the simulation of the test canal tube in **Figure 5**.

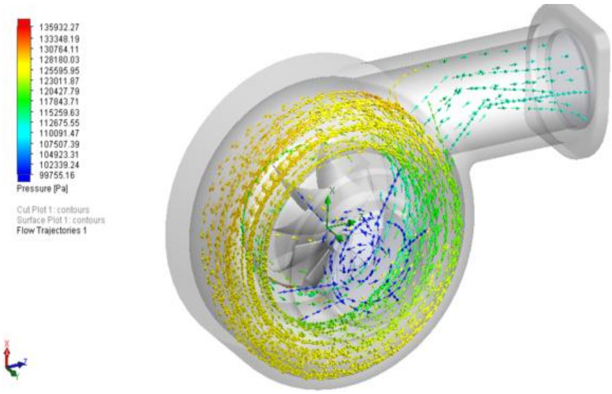

Figure 5 Flow simulation of test canal tube

The simulation of the test canal tube shown in **Figure 5** is one method used to improve the efficiency; it does allow buckets of the Eco-wheel to be filled ≥ 50% making weight a factor of faster rotation for the wheels. The experimental results obtained from the Eco-wheel optimisation proves that the design is efficient and would be very useful to the 3D renewable sustainable power station. It is however important to mention that there is a possibility of implementing a 2D system as well thus juxtaposing solar PV systems technology with Hydroelectric for example, the advantages of this would then be a higher total delivered output power as energy will be generated from two renewable sources. The disadvantage however of having a 1D and 2D as compared to a 3D system is that the geographical conditions and locations are not always ideal for a 1D or 2D system hence the necessity for a 3D system where the energy produced by the hydro system could be used to feed the wind turbine, causing a rotation that will generate energy at all time.

III. MICRO-HYDROPOWER ECO WHEEL SYSTEM DATA ANALYSIS

Considering efficiency estimation for the overshot, undershot and breastshot wheels, it was apparent to consider efficiency improvement of the Overshot water wheel. Offering an average of 80% already, this could be scaled up by taking a step by step approach of the designs with careful measurements and calculations. The aim of this design is hence to offer a much efficient overshoot water wheel that could offer a higher efficiency than what is already being obtained currently with careful material selection making the overall design very affordable by all standard. This will then be preferred than other designs considering efficiency improvement and affordability. A wide range of theoretical calculations will be done to determine the efficiency and flow simulation carried out using Solid works. The unit will then be practically built and used for a 3D Renewable sustainable Power station with Low cost and high efficiency. The design of the micro-hydropower began by considering the test tube in which the wheel will be tested. These measurements were then taken and used in the CAD design using Solidworks. A flow simulation of the micro-hydropower was done with results presented in **Figure 5**. Calculations and measurements considerations can be obtained in the Appendix section of this paper.

IV. Experimental Test & measurements

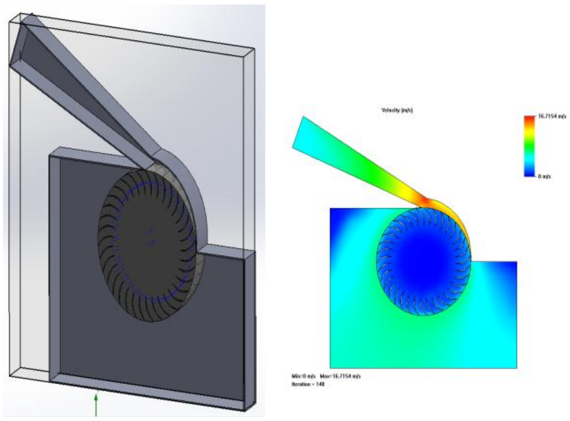

Figure 6 Overshot waterwheel powered by gravitational potential energy, with buckets tips out at angle θ

The considerations to getting the overall efficiency of the wheel will have to incorporate unavoidable realities such as the water momentum, probable spillage of the water and friction. One can then assume that the buckets in **Figure 6** are at angle of θ where $0< \theta \leq \theta_1$. The buckets are at an angle of Δθ around the wheel so one could say that Δθ= 2π.

Considering that the mass of the water in each of the buckets is

$$\Delta m = \rho f \times \Delta t \quad (1)$$

where ρ represents the density, f is the flow rate and Δt the time interval taken to fill the next bucket on the rim. This is obtainable by equating equation $\omega \Delta t = \Delta\theta$ with ω representing the waterwheel angular speed hence the equation will be

$$\Delta m = \frac{\rho f}{\omega} \Delta\theta \quad (2)$$

Considering that the mass of the water in each of the buckets is $\Delta m = \rho f \times \Delta t$ where ρ represents the density, f is the flow rate and Δt the time interval taken to fill the next bucket on the rim.

In order to obtain the efficiency, one needs to understand that the theorem of force applied on a body is obtained by the controlled volume of fluid exerted, which is similar to the rate of change of momentum, the theorem can be conveyed as

$$F = Mout.Vout - Min.Vin \quad (3)$$

Where M represent the mass flow rate earlier obtained, F the force exerted by the water on a solid body, the total force exerted in the procedure could be expressed as

$$F = F1 + F2 + F3 = Mout.Vout - Min.Vin \quad (4)$$

F1 stands for the force of the fluid on the buckets, F2 the returning force of the buckets on the fluid and F3 the force of the fluid exerted outside the control volume. These different forces need to be in the analysis as the equation can be simplified by the simple understanding that the reaction force is equal to the main force applied in the first instance by the water on the bucket but in different direction. This could then be neglected due to gravity and the assumption made that the pressure of the water is maintained at a constant which will make F2 &F3 equal to zero. This now gives the clear understanding of the role of gravity and the two direction in which the waterwheel rotates in;

- *Considering*

$$Direction\ (x) Rx = m.(Vin - Vout) \quad (5)$$

$$while\ in\ Direction\ (y) Ry = m.(vin - Vout)y \quad (6)$$

- *The resultant for Direction x and y can be expressed as*

$$R = \sqrt{R_x^2} + \sqrt{R_y^2} \quad (7)$$

- $According\ to\ Newton's\ Second\ Law\ of\ Motion$

$$F = m(vt - Vi) \quad (8)$$

Using the above equation, mass flow rate= 24.816 m^3/s, Vi= 0.8344 m/s, Vt= 44.23 m/s

$$F = R\ due\ to\ F2\ \&F3 = 0$$

$$and\ the\ resultant\ force\ being\ equal\ to\ the\ reaction\ force = 1076.9\ N$$

The total input power will then be considered as the total sum of the input force on each bucket and the water flow rate applied on the buckets enabling a constant rotation, this could be found by applying

$$Pi = \sum \int_{\theta_i}^{\theta_f} R\, d\theta \quad (9)$$

Where Pi= Input power; θ_f is the final angular displacement; θ_i is the initial angular displacement and $d\theta$ represents the change in angular displacement

$$Pi = \sum \int_{\theta_i}^{\theta_f} R\, d\theta = 1076.9 \times \frac{\pi}{4} = therefore\ Pi = 845.79\ watts$$

The mechanical efficiency of the wheel could then be determine by applying the formulae

$$Efficiency = 85.3\ \%$$

V. RESULTS & DISCUSSIONS

The choice of turbine type, size and speed is based on the net head and maximum water flow rate, which must be determined by the river or stream, in our case, a canal tube where the turbine shall be installed. Because of micro-hydro-electric power turbines are normally built as run of the flow of water, the maximum water flow capacity of the turbine must be determined by mean of the flow duration curve for the canal. A way for organizing discharge data is by plotting a flow duration curve, that shows for a particular point on a river the proportion of time during which the discharge there equals or exceeds certain values. It can be obtained from the hydro-graph by organizing the data by magnitude instead of chronologically. The mean annual flow gives an idea of a stream's or water power potential. Flow Duration Curves can be produced for particular periods of time as well as for particular years. A Micro-Hydro power using an Eco-hydro wheel has been developed and presented in this paper. Initial investigations showed that Overshot water wheel have an average output efficiency of 80% generally which was improved due to a much clever design and mathematical approach which enabled efficiency improvement. The CAD design presented on here shows that design specifications and angular measurement considerations impacts the outcome of the efficiency. The test run and theoretical evaluations showed that the new eco-wheel design gave an estimated output of 85% efficiency which makes it a much improved and efficient eco-wheel design than the average overshot water wheel earlier presented in this paper. The technical limits remained in the design of the cells used for the wheel design as they retained more than 25% than what previous literature and initial investigations proved of the water making gravity to react on the cells and forcing more rotation. Testing the wheel also revealed that the wheel is capable of delivering electrical power close enough to the estimated efficiency of the new design.

VI. CONCLUSION

When the turbine and generator operate at the same speed and can be placed so that their shafts are in line, direct coupling is the right solution. Virtually no power losses are incurred and maintenance is minimal. The presented design offers a much more interesting approach to hydropower generation and should contribute to developing and developed countries green economy as a means of providing green energy supply leading to a much reduced cost of energy and the reduction of carbon emission rate caused by the constant burning of fossil fuels and the reliability on them by generating stations for power production. Micro-hydro power continues to grow around the world, it is important to show the public how feasible micro-hydro systems actually are in a suitable site. The only requirements for micro-hydro power are water sources, turbines, generators, proper design and installation, which not only helps each individual person but also helps the world and environment as a whole.

The choice of turbine will depend mainly on the pressure head available and the water flow rate. There are two basic modes of operation for hydro power turbines: Impulse and reaction. Impulse turbines are driven by a jet of water and they are suitable for high heads and low flow rates. Reaction turbines run filled with water and use both angular and linear momentum of the flowing water to run the rotor and they are used for medium and low heads and high flow rate which was demonstrated in this paper.

The design presented certainly focuses on a micro-hydro generator but the ideologies expressed in this paper are not limited to a small scale power production as the topology used in the design could be applied on a bigger scale and generate enough energy capable of meeting the needs of a whole industry. The work presented in this paper is not complete in the sense that more refined modelling for items such as the flow simulation of the overall system have to be completed and compared with a field test data and results for verification of the results obtained from the simulation and possible adjustment of the design if collective results do not agree with each other. Further research and development will also consider the business aspect of this prototype with a framework mapping out the necessary action to uptake and clarifies the impacts of the model on mini and major hybrid systems considering cost and significant economic advantages

REFERENCES

[1] IPCC, 2007 Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press Cambridge, UK

[2] International Energy Agency (IEA) (2010), Energy Technology & Hydropower generation Perspectives 2010, IEA, Paris

[3] EPRI (Electric Power Research Institute) (2006), Hydro wheels self-reliance, experience with micro Hydro generators, a US micro Hydro Power Technology Report, Volume 2, New York, US

[4] WEIDNER C.R., 2003, Overshoot water wheel design, Theory and test of an overshoot water wheel, Bulletin of the Wisconsin University Issue No. 529, Engineering Series, Vol. 7, No. 2, 118-290.

[5] Kauppert et al 2003, water wheels Efficiency Curve,– Britain's new source of energy, Proc. ICE Civ. Eng., Vol. 150, No. 4, 178-186.

[6] Watts. M, 2010 Design considerations of the overshot water wheel; Princes Risborough, UK: Shire-Publications, Cambridge, UK

[7] Cook, T.C., G.E. Hecker, H.B. Faulkner, and W. Jansen. 1997. Development of a more fish tolerant Turbine runner-advanced hydropower project hydroelectric power efficiency improvement

[8] DOE/ID-10571 Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho, US

[9] OSSBERGER, 2012 A study conducted on the Efficiency curve of the Kaplan turbine, [accessed on April 11, 2014] VIEW ITEM

[10] EPRI (Electric Power Research Institute) (2006)Hydro wheels self-reliance, experience with micro hydro generators, , Rehabilitating and Upgrading Hydro Power Plants - a US micro Hydro Power Technology ound-Up Report, Volume 2, New York, US

[11] Overshot water wheel buckets design specifications MÜ LLER W., 1939, Die Wasserräder, The water wheel, Reprint of the 2nd Ed, Moritz Schäfer Verlag, Detmold, 2009

[12] Muller W. 2003, Overshot water wheel buckets design specifications, Die Wasserräder, The water Wheel, Reprint of the 2nd Ed, Moritz Schäfer Verlag, Detmold, Germany.