Adaptive Micro-tubular Turbines for Variable Flow Conditions in Agricultural Water Systems

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Abstract: - Micro-tubular turbines are compact hydroelectric devices engineered to generate electricity from submerging in flowing water, providing a sustainable energy solution for farms with access to streams, rivers, or irrigation canals. These turbines enable off-grid energy generation, allowing farms to maintain large areas efficiently and independently of grid power. Each turbine comprises a cross-flow propeller enclosed in a tube and connected to a generator, making it a cost-effective method for harnessing electricity from low-head water sources. This study examines the application of micro-tubular turbines in water sources with heads ranging from 0.2 to 2 meters, assessing their performance under these specific conditions. To optimize turbine efficiency and power output, Computational Fluid Dynamics (CFD) modeling techniques are applied to refine turbine blade designs. CFD simulations analyze fluid flow dynamics around the blades, facilitating the identification of optimal blade geometry and operating parameters for low-pressure environments. These optimizations ensure the turbine can effectively match specific range of water flow rates and head levels, enhancing energy efficiency. Micro-tubular turbines' compact size simplifies installation across varied farm sizes, with flexible placement options directly in water sources or on platforms above. Minimal maintenance needs and extended lifespan make them a cost-effective, environmentally friendly investment for farmers, significantly reducing energy costs and carbon emissions.

Key-Words: - Micro-tubular, Hydroelectric, Cross-flow, Low-Head, Blade Designs

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1 Introduction

This hybrid top borer type, according to the sugarcane community, is far worse than it was five years ago. In the plant and ratoon crop data, Indonesia shows that insect pests such as top borer, shoot borer, and stalk borer are dominant and have a 24.4 to 32.3% impact on yields and damaged percent [1]. In India, the yield loss is 21 to 37% [2-4]. While in our impacted areas, such as Malaysia, it is around 30%, even with manual control and pesticides or biological control data collected from local sugarcane community. These pests are very difficult to control as the main problem is that the pests lay their eggs on the sugarcane buds, which then turn into larvae that absorbs all the sweetness in the sugarcane. After absorbing it, it burrows in the sugar cane. Data from the sugarcane community in Malaysia shows that the greatest losses are incurred between one and three months after harvest. The female lays about 300 - 400 flattened eggs in different clusters on the underside of the leaves [5]. The eggs hatch within five days. The larvae bore into the trunk above the ground,

within the central branch, and obtained food from that location. It possesses a gold hue covered with five purple stripes and exhibits brown streaks.

One successful integrated pest management strategy is the use of light traps to manage major pests, such as the sugarcane top borer [6]. To decrease the number of larvae hatching in the field, farmers take the basic light trap concept to attract the adult borer to settle on the trap and die before depositing its eggs [7]. Feedback from the sugarcane community: the implementation of light traps can have a significant impact on lowering top borer populations in sugarcane fields. This resulted in enhanced yields and improved crop quality [8]. Also, this method is free from any harmful effects on the environment [9].

Observations of the sugarcane field at the Ayer Hitam Agricultural Center area during the windy season revealed that colonies of borers moved to the local sugarcane field downwind. Insecticide must be regularly sprayed on the whole field of sugarcane, which is the first step. It was found to be unable to deter the species and was affecting sugarcane stalk production and quality. Use bug lights only at night to find and eliminate known locations during the day. The demands of the process are exhausting, and it's important to have a mobile trap that can travel across regions and collect data. When using commercially available batteries, it can only light for about an hour. Generators running constantly at night are predicted to expand the operating area.

Farmers report that the small, transportable, and easy-to-install hydroelectric generators have greatly improved power supply, especially in large and uneven areas. This kind of hydroelectric generator helps deal with a lot of the issues that traditional energy sources affect. Because hydroelectric generators are small-sized and easy to carry, they can function in remote places. For so long, hydroelectric generators have gained remarkable popularity due to their easy installation. They can be put up quickly without elaborate and costly construction works. Farmers and communities can quickly create energy from water sources around them to produce electricity to provide for their needs. Small hydro generators can be used for a variety of purposes and are not restricted to any certain area or landscape. These generators can be customized for use in hilly, mountainous areas where there is fast-flowing water and also in flat areas in irrigation canals. They have the flexibility to be used as an available energy option in different lands.

If managed properly, water is naturally renewable and can be and remain a source of constant power. Moreover, farmers who depend on energy to carry out agricultural activities like watering, processing, and lighting benefit especially from this. The cost of small hydroelectric generators is cheaper than the large ones. Using small hydro strong electrical generators reduces the initial costs as well as annual costs, which are affordable to farmers. The low price of these generators enhances their chances of broad acceptance and influence. All in all, this small, portable, and easy-to-install hydroelectric generator is truly changing the game for powering large and uneven spaces. Through exploiting energy from the surrounding water, farmers and communities can acquire continuous and sustainable electricity for extra income and production.

2 Literature Review

In recent years, the use of small hydroelectric generators for agricultural areas has become a major interest. Especially ditches less than 2 meters deep [10]. Micro-hydro used by agricultural farmers refers to small-scale hydroelectric systems that are installed in agricultural areas to generate electricity. Micro-hydro with blade type by channels, Pelton turbines, and propeller turbines are capable of harnessing energy from modest water resources, including streams and irrigation ditches. They are also easy to install and operate, having a low impact on the environment, hence a feasible and sustainable solution for rural electrification [11].

The research by [12] is a valuable and comprehensive overview of micro-tubular turbines in agricultural ditches of less than 2 meters deep. A beginning description is given of the challenges farmers face regarding energy costs and sustainability. The authors have introduced the idea of micro-tubular turbines. These are small hydroelectric generators that generate energy by the force of the water. The use of micro-tubular turbines at trench depths up to 2 m in agriculture is the focus of the evaluation. Scientists have shown that these turbines are designed specifically for a particular flow and head of the water. Their technologies improve efficiency and adaptability to various farm needs.

Many experts also stated the benefits of using micro-tubular turbines in low water sources. A major benefit of utilizing these turbines is to provide clean energy, thus reducing reliance on grid electricity and cutting down on a small portion of the carbon footprint [13]. Moreover, micro-tubular turbines frequently have a low cost and require little maintenance, making them a wise long-term investment for farmers to reduce their energy bills [14]. The researcher examines tubular turbines for

use in extra-low head hydropower. The focus of the study lies on their structure and performance optimization. In addition, cavitation performance scrutiny, duct-casing design, and the influence of the nozzle adjustment on the changing seasonal flow rates are practically being analyzed [15]. The presentation on the micro-tubular turbines in agricultural ditches less than 2 meters deep was quite interesting. It provided viewers an insight into how farmers can reduce energy bills along with shifting towards a more sustainable possible future [16].

Micro-tubular turbines (also called submerged micro-turbines or micro-hydro turbines) are water turbines that are fully submerged in water. Blade design for micro-hydro turbines in agricultural ditches faces unique challenges due to dynamic environments with soil erosion and fluctuating water levels. In such conditions, blades must be robust, corrosion-resistant, and adaptable to varying flow rates and sediment loads. Advanced designs incorporating composite materials or coatings can enhance durability and efficiency. Optimizing blade geometry such as curved or adjustable blades which can improve energy capture in low-head, turbulent flows. Additionally, self-cleaning features can mitigate clogging from debris. Research into adaptive blade designs that respond to real-time environmental changes could further enhance performance, ensuring reliable energy generation in these challenging, erosion-prone, and variable-depth water systems.

3 Optimizing Blade Design

If this is observed, a continuous generator will need to be used to light a 120-watt white bulb on the affected area for 10 to 11 hours. The drainage water supply is the most easily accessible in a farming region and has vast resources. There is also a local survey of solar and windmill use, but it is not comprehensive enough to provide at least 10 full hours of power. This is where research began to develop blades that would be best placed in the drainage water sources of the Calvert Channel. There are several limitations in defining the blade shape [17]. For example, turbines on the market cannot rotate continuously without human adjustment. This is caused by the splash of water and the inertia of vibration during reverse rotation [18, 19]. As a result of this incident, further monitoring data was required, and it was necessary to ensure that the shape of the runner blades conformed to the structure of the channel [20-26]. The amount of dirt will also affect the smoothness of the blade [27]. Our research starts with these two criteria.

Agriculture is increasingly interested in harnessing the power of water to generate electricity using micro-hydro blades. For distributed power generation in rural areas, these small water turbines are a viable option [28]. However, a major concern in the farming community is the limited efficiency of submersible micro-hydro blades, especially in fields with shallow spring water sources [29]. All of the hydro blades discussed in this community seem to be market products. The rotor blades low depth can't spin as efficiently as they could and generate less of an overall power output. Research and inventions are required to get over this problem to make small hydro blades work better under these conditions. If we can understand the site-specific constraints and apply proper solutions, then the efficiency and profitability of the small hydropower plants in agricultural areas with shallow spring water can be improved.

The market propeller fitted with hydro-blades is unable to get continuous rotation. The blades get stuck because they keep gripping water all through the rotation, and then inertia and earth gravity generate vibrations that do the stopping [30, 31]. This raises the question of how to design a blade that does not hold water while spinning and is able to accelerate to the optimum level, mainly in agricultural ditches [32-34]. Based on this finding, an attempt was made to determine the flow of water in the farm front drain in another mountainous area with a slope of 15 degrees or more. Although the water thrust at this location is constant throughout the year, tolerance measurements must be taken where the maximum and minimum water heights can be achieved in order to design the blades that are joined during spinning [35].

This problem indicated the need for a generator that runs continuously at night to provide continuous power to furrows in the field for battery charging stations or for wiring in areas bordered by ditches. The efficiency of these turbines is usually limited by the design flow, which tends to decrease when the turbine is operated at low flow [36]. This makes these turbines more suitable for locations with a uniform flow profile. These turbines are also suitable for closed systems where back pressure is required [37].

For different types of water pipelines, traditional and modern turbine technologies are available. Although turbines are classified according to their likely line location, there is still considerable overlap in their actual use [38]. For example, a potential hydroelectric plant near diversion structures may require reduced water flow. This situation is possible in different types of lines; therefore, existing or future developers should consider turbines other than those specified. Understanding the site characteristics as

well as the configuration in which it is actively involved (whether air pressure or in-line discharge) is critical when selecting the appropriate turbine [39]. Hydropower developers can take advantage of the system by properly understanding the system and choosing to provide the most cost-effective turbines.

It is vital to stress, however, that the availability of renewable energy from existing water conduits must remain a secondary role of the asset. The primary goal of every utility is to supply consumers with consistent and dependable current delivery [40]. Nonetheless, it should be emphasized that the current generation of turbine technologies has the potential to provide more cost-effective solutions due to their modular structure, which lowers the cost of powerhouse building [41].

However, it needs to be emphasized that the availability of renewable energy in existing water mains must remain a secondary role for the asset. The primary goal of every utility is to supply consumers with consistent and dependable current delivery. However, it should be emphasized that due to their modular design, the current generation of turbine technology has the potential to provide more cost-effective solutions, reducing the cost of building mini generators [42].

3.1 Turbine selection

According to the data in the sugarcane field test area, high-power bulbs alone cannot attract all kinds of insects, especially our target top borer; heaters are needed. This information comes from the first insect trap prototype, which used a 120-watt white light connected directly to a diesel generator, which was found to be very warm when turned on. Therefore, the simplified analysis cannot accurately simulate what happens when LED bulbs are used instead of incandescent bulbs (included). A possible problem is heat transfer to the base. Part of the reason the bulb is inefficient is that it emits a lot of infrared light, which, while it doesn't let us see, creates heat that isn't stored in the bulb. The LED base has some electronic components and most of the inefficiency of the bulb is transferred to the base as heat. Therefore, choose a 120-watt bulb with a temperature of 27 degrees Celsius, as warmth will attract insects [43].

Bulb lights or other everyday devices can be powered in different ways. Using a wet battery is a process. It is the most common type of power supply. It's called a "dry battery" because it contains chemical paste and no liquid. Dry batteries are popular because they are cheap, affordable and highly available. The main problem is that it cannot supply power for a long time, and it cannot be charged when it is out of power. It must be replaced with a new dry battery to maintain the functionality of the device. High loads, especially 120-watt electrical equipment, make continuous battery operation impractical. In the next stage, the battery cannot be recharged, and internal damage to the materials used as anode and cathode is inevitable. From this observation, we conclude that the need for continuous resources, such as a generator that consistently supplies energy, depends on a good controller. To fully explore the potential of sugarcane harvester control improvements, it is important to consider the specific challenges and requirements of the harvesting process [44, 45].

This micro-generator is a system designed to use small generators (with a target capacity of up to 120 watts) to power light traps and fences. The system is typically deployed in rural areas without access to the main grid. It is made up of a small generator, battery, inverter, and charge controller. The electric energy generated by the generator goes to the battery. The charge controller ensures proper management of current flow between the generator, battery, and inverter. It prevents inefficient charging and overcharging of the battery. The inverter, then the battery's DC supply, gets converted into an AC supply, which is then used to power light traps and fences. Insects that are drawn to the light can then be trapped for research purposes and many other uses. Fences are barriers often placed in a variety of areas to keep animals away. Using micro-generator power systems for light traps and fences, both of them need power. This micro-generator powers electric fences and electric gates to keep animals from certain areas like your garden and your farm.

As per the above, it can be inferred that a turbine will generate a suitable water source. Usually, the type of turbine that is appropriate for the environment is mainly a function of the head and flow of water available at the site [46]. The hydro turbine will be constructed based on its specific speed correlate with low depth. The section outlines the important factors to consider when selecting a turbine and the basic equations that give necessary information regarding the relative speed and dimensions of various turbines [47]. Innovation and field testing discovered that water sources in agricultural areas exhibit low storage rates and slope downward. The original design of the system employs the propeller type, fixed pitch one. It is packed in the conduits made from PVC substances to rise with the thrust and to defeat the certain problem of continuous rotation [48-50]. But the performance was not stable and had to be manually adjusted due to dirt sticking to the blade.

Recently, a common alternative, micro-turbines, has become a focal point in small scale hydro power applications across the world. One place that is

particularly suitable for them is the case of low head water sources such as the sea, streams, and irrigation canals. Not only are they compact and efficient, but also clean since they do not emit any noise or pollution [51-54]. The cross-flow type in particular, which is very often referred to as hydroelectric tube turbine, because of its efficiency and the fact that it requires minimal maintenance, has captured the attention of the super-efficient micro-turbines community. This specific type of turbine that is a cross-flow design allows the water to come into contact with the blades twice, at a location usually known as the inception stage, which results in a higher rate of energy transfer and, as expected, efficiency is improved. Further, the growing manufacturing industry has enhanced the adaptability of the cross-flow micro-tubular turbines, thus it is possible to tailor them to certain site conditions and make them most suitable for such remote and agricultural areas.

Amongst the other low head turbine systems, cross-flow turbines are more efficient than Kaplan, Gorlov, Archimedean screw, and Banki-Michell ones in terms of cost-effectiveness and their ability to handle varying water levels. Kaplan and Gorlov turbines are effective but are more complex and require a sophisticated blade design in the case of varying water flow conditions [55]. On the other hand, the simpler, shockproof cross-flow turbine is excellent at various head heights and source water flows, such as 0.3 to 1.5 m^3/s and an average canal flow velocity of almost 1 m/s. This inevitably makes it suitable for regions with agricultural land that can use both the said irrigation canals and streams for sustainable energy production, thus, rely less on the power grid. As a scalable, renewable energy solution, cross-flow micro-tubular turbines not only contribute to energy self-sufficiency in agriculture but also represent a promising technology for small hydropower projects worldwide [56].

Specific flow rate can be estimated mathematically as a function of maximum power and net head (denoted as) or flow rate and net head (denoted as) [57]. The speed Ns determined in the first example is the turbine speed (RPM) operating at 1 m head and delivering 1 kW as shown in Fig. 1. Once the turbine type, specific speed and net head are determined, the basic size of the turbine can be calculated. Each species has its own unique shape and structure, as shown in Fig. 1. Therefore, there are multiple dimension equations depending on the shape and operation of the turbine [58].

To improve the system's functionality, a separation is introduced where one generator motor operates independently while the other focuses on the turbine blade housed inside a PVC pipe. The PVC housing is essential for curbing debris drifting in the ditch, preventing it from entangling with the blade. Uninterrupted turbine operation is a mechanism for reducing maintenance needs by blocking sediments and floating materials. The system is cutting the generator motor off and shielding the turbine blade; thus, this system is precise and will always be good in all environmental conditions.

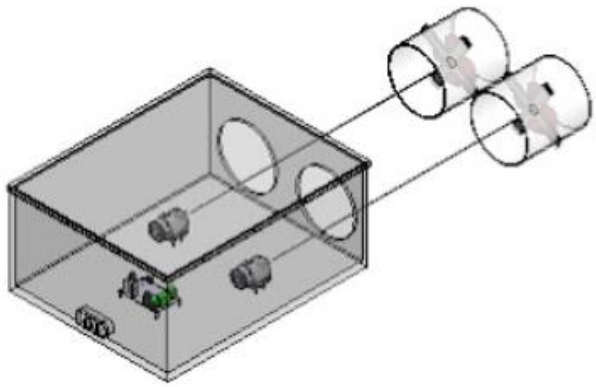

Fig. 1 Micro-tubular turbine external geometry

4 Analysis Simulation Water Flow

In order for a micro-tubular turbine to float in the water that is swallowed. The designer must take into account a number of factors, including as the turbine's weight and size, water flow, and the initial power generation quantity, Here are the steps to design and select the micro-tubular turbine for this purpose. First, determine the water flow rate by measuring the amount of water swallowed and the time it takes to swallow. These figures tell us approximately how much power a micro-tubular turbine can produce. Then calculate the power output based on the water flow, size of the turbine, and the efficiency. The power that is needed for a certain task can then be estimated, for example, by charging a device or operating an electric fence. Choose the suitable size of the turbine on the premise of the necessary power and water flow. The utility software for the turbine design can be employed to find out the best size for the particular case.

The turbine efficiency is calculated by turbine design software to ensure that the turbine is able to generate the maximum power with the help of the same volume of water. Lightweight and corrosion-resistant materials were picked for the micro-tubular turbines to resist harsh conditions brought about by water swallowing. As a result, prototype turbines are

now manufactured and used to test and estimate the actual water power generated or recognize the possible deficiencies in the design or the performance. In particular, the process of designing and selecting micro-tubular turbines for the flotation operations under swallowed water conditions requires critical thinking of several variables. With well-thought-out design and problem-solving, it is possible to generate electrical power by means of a micro-tubular turbine to treat a wide range of water-related cases, such as swallowing water.

When designing the propeller of a micro-tubular turbine operating at a water velocity of 0.35 m/s at a water depth of below 1.5 m, the following measures must be taken. The Reynolds number must be looked at to find out what conditions lead to turbulent flow, and the release of dye is used to see how the water flows. One can estimate the amount of power needed to perform a specific task, such as charging and opening rows of electric fences, to determine the required power output. The product of the water velocity and the cross-sectional area of pipe with a diameter of 10 cm gives the water flow rate. For a pipe of 0.1 m diameter, the cross-sectional area can be calculated as 0.00785 m2. Therefore, the water flow rate is 0.00275 m3/s.

A suitable micro-tubular turbine design was selected based on the required power and water flow. Turbines should be designed to operate efficiently at the required water velocity and water depth. Blade tip speed is an important factor in propeller design as it determines the maximum rotational speed of the propeller. Tip speed should not exceed certain limits to avoid cavitation and other failures. The recommended maximum tip speed is about 50 RPM and above.

The selected locations reflect a variety of locations with different mean water columns and velocities. Three water turbines are simulated at each location. First measure the water flow, and then measure the geometric dimension parameters of the selected small water turbine. The design CAD software was then used to incorporate the efficiency, power output and energy of the small hydro turbines at all sites into the final element. These stages are detailed in the following subsections.

Computational Fluid Dynamics (CFD) can be used to determine the optimal blade pitch step size for a micro-tubular turbine. Turbine blade Radial-Inflow Turbine (RIT) performance is enhanced by CFD simulations, which can give a complete insight into the fluid flow around the rotor, and thus the pitch of the blade can be optimized for the best turbine efficiency. The basic steps include developing a 3D model of the micro-tubular turbine together with a CFD tool such as ANSYS Fluent or OpenFOAM. The computational meshing should be applied to flesh out the micro-tubular fluid channel, and the grid system is used to discretize the domain in order to solve the governing fluid flow equations. Fluid flow simulations using different blade angle steps are conducted to determine the blade angle that allows the maximum efficiency [59]. The turbine efficiency can be estimated by dividing the power output by the input power necessary to drive the turbine [60]. After the correct blade angle is checked, the next stage in the fabrication process will include the design and manufacture of a micro-tubular turbine to the desired blade angle stage. CFD is also a powerful tool to simulate the performance of the manufactured turbines to check the design.

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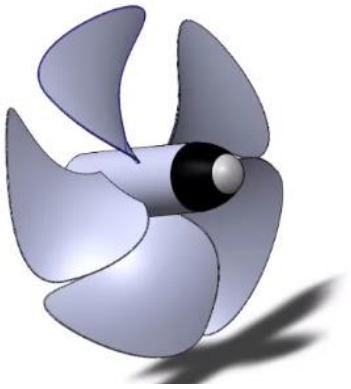

Fig. 2 3D model of micro-tubular turbine blade

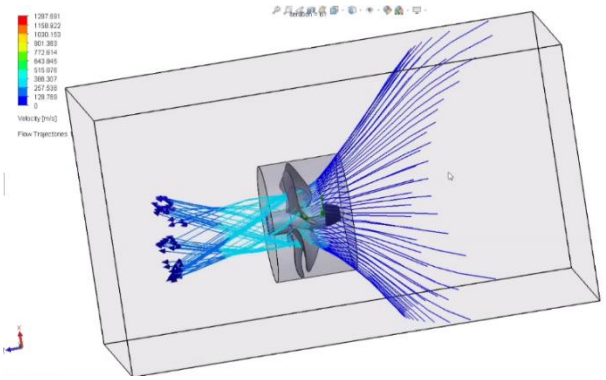

Fig. 3 Computational Fluid Dynamics (CFD) for determine blade angle simulation flow step full

The blade angle of a micro-tubular turbine in CAD is determined by several factors, including water velocity, depth, and flow path. Fig. 2 shows the blade design, illustrating the geometric configuration and angle considerations. Here are some design tips for determining blade angle. Find ideal Top Speed Ratio (TSR). The perfect TSR is the tip speed to water speed ratio. Usually, a 4 - 6 TSR is the ideal condition for micro-tubular machines. Optimal RPM and blade diameter can be easily calculated. Also, the blades of micro-tubular turbines are generally at an angle of 20 to 30 degrees. The angle is measured in relation to a plane that is perpendicular to the axis of rotation. However, the correct blade angle might change if the design specifications are unique.

Finally, let's analyze the flow paths. The blade angle should be configured in such a way as to take out energy effectively. This calls for a detailed analysis of the flow routes, which may be done through the use of flow modeling techniques such as Computational Fluid Dynamics (CFD). Figure 3 is a diagram representing the CAD analysis of the turbine, which pinpoints the impact of blade angle on flow efficiency and energy capture. The turbine performance can be validated by testing the blade angle design in CAD and then in a flow cell or other test environment. This makes it easier to determine the best blade angle and optimize the designs to attain the maximum possible energy extraction.

One should keep in mind that the perfect blade angle relies on several factors like exact water velocity, depth and flow direction.. If the user is not sure about the best angle for the specific design, it is wise to thoroughly analyze these parameters and consult an experienced specialist or a specific simulator. During the process of making the generator work, the user has to put the utility generator's fan in a running stream. It will be good to allow the fans in the mountain streams and normal streams sit firm at the beginning of the research. The second step is to estimate how long it will take the battery to fully charge. The final step is to check that the handheld generator can withstand the vibrations of the spinning fan blades. This testing is done to guarantee the durability and flexibility of the product.

4.1 Turbines Output Power and Energy

This chapter analyzes the performance and mechanical characteristics of the generator set using data from a series of tests. The generator was thoroughly inspected and evaluated against the stated objectives. This chapter presents the shape and design of the final generator to better understand the mechanism and shape of the final product. Provides how-to and product development costs to explain how to use the features of this generator.

Flow and head are two factors that affect hydroelectric power generation. The power produced by the turbine can be calculated independently of the water flow through open channels or penstocks using references:

$$P = \rho g H_n Q \eta_t \quad (1)$$

Where:

P_t power in Watt generated in the turbine shaft.

ρ water density (1000 kg/m^3).

H_n net head (m).

Q water flow rate (m^3/s).

g gravity acceleration constant (9.8067 m/s^2).

η_t turbine efficiency (normally 80–90%).

At the turbine shaft, a turbine turns water pressure energy into mechanical energy, which powers a linked generator to generate electrical energy.

Turbines that are designed for hydropower mostly depend on blade optimization. The basis of the advanced hydrodynamic and fluid dynamic principles that are necessary to correctly modeling of turbulent flow, cavitation, and blade-induced vortex dynamics [61]. The functionality of the turbine and thus the exploitation of energy can be achieved by properly modeling the turbulent flow, cavitation, and vortex dynamics of the blades, and this is possible with the new study. This report looks at advanced modeling approaches, among which are Computational Fluid Dynamics (CFD), Blade Element Momentum Theory (BEMT), and the empirical modeling of blades, to improve the blade's performance. It is such tactics that technicians can use to make sure that hydro systems produce high energy in multiple application areas.

4.2 Advanced Hydrodynamic and Fluid Dynamics Principles for Hydro Turbine Blade Optimization

The optimization of a hydro turbine blade is the process of employing the most modern techniques of hydrodynamics and fluid dynamics. The project team

used the most advanced software and hydrodynamic model of equation or Computational Fluid Dynamics (CFD) to solve the complex issue. The simple models, such as the Navier-Stokes and Blade Element Momentum Theory (BEMT), are the first ones to be solved in a CFD simulation in order to produce the basis for predicting and optimizing the lift, drag, and flow around the blade [62]. Besides, engineers also perform the particular techniques, which are Blueprinting Fluid Dynamics (BFD) and empirical modeling, to estimate and further analyze the effect of cavitation. These ultimate methods lay the foundation for the turbine's power output and operational stability, which are the main issues in varied hydrodynamic conditions.

To evaluate fluid motion around turbine blades, which is particularly important during turbulent times, one must understand the Navier-Stokes equations. The incompressible version of these equations summarizes the fundamental elements in the field, aiming at depicting the very complex fluid flow behavior:

$$\boldsymbol{\rho}\left(\frac{\partial \vec{v}}{\partial t}+\vec{v}\cdot\boldsymbol{\nabla}\vec{v}\right)=-\boldsymbol{\nabla p}+\boldsymbol{\mu}\boldsymbol{\nabla}^{2}\vec{v}+\vec{f} \quad (2)$$

viscosity, and $\vec{f}$ the external forces such as gravity. To solve these equations in turbulent scenarios, practical applications often employ Reynolds-Averaged Navier-Stokes (RANS) or Large Eddy Simulation (LES) methods, which give a high-fidelity turbulence field. One of the results is a blade shape with the lowest losses induced by turbulence changing, thereby, of course, the requirement for increasing efficiency.

4.3 Advanced Hydrodynamic and Fluid Dynamics Principles for Hydro Turbine Blade Optimization

The calculation of the lift (L) and drag (D) forces is critical for maximizing the efficiency of the blade. Dynamic stall, which is the main cause of the lift and drag forces variability that arises as a result of the cyclic motion and variable angles of attack of turbine blades, is an elusive factor. It is represented as:

$$\boldsymbol{L}=\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\rho V^{2}C_{L}(t)A}$$

$$\boldsymbol{D}=\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\rho V^{2}C_{D}(t)A} \quad (3)$$

$C_L(t)$ and $C_D(t)$ represented as coefficients in the time domain that relatively related to hysteresis effects caused by dynamic stall. According to these scenarios, the blade's performance improves under wide range of operating conditions . This is achievable with models such as the Leishman-Beddoes model, which makes it possible to identify hysteresis effects prior to the actual stall, thus enabling the prediction of transient effects.

The method of dynamic stall also has real-life applications in open channel flow, for instance, in Calvert streams, where the end-depth method is a more affordable way to assess the discharge. The method is practical because the channels could be designed in such a way that a free overfall comes off, and the natural channels such as waterfalls typically have such setups. Unlike installing a weir or flume, which incurs substantial costs, measuring flow rate using the end-depth method minimizes expenses and leverages the natural channel design for efficient discharge calculation. This combination of low cost and practicality makes it particularly appealing for stream flow measurement in remote or natural settings.

4.4 Cavitation Dynamics Using the Rayleigh-Plesset Equation

In high-speed hydro turbine applications, cavitation presents a critical challenge. The cavitation number σ quantifies the potential for cavitation occurrence:

$$\boldsymbol{\sigma}=\frac{\boldsymbol{p_{\infty}-p_{v}}}{\mathbf{0.5}\cdot\boldsymbol{\rho}\cdot\boldsymbol{V^{2}}} \quad (4)$$

Cavitation behavior around the blade can be modeled using the Rayleigh-Plesset equation for individual cavitation bubbles:

$$\frac{\boldsymbol{d^{2}R}}{\boldsymbol{dt^{2}}}+\frac{\mathbf{3}}{\mathbf{2}}\left(\frac{\boldsymbol{dR}}{\boldsymbol{dt}}\right)^{\mathbf{2}}=\frac{\boldsymbol{p_{\infty}-p_{v}-p_{\mathrm{cav}}}}{\boldsymbol{\rho}}] \quad (5)$$

where R represents the bubble radius, p_{cav} the pressure within the bubble, p_{∞} the far-field pressure, and p_v the vapor pressure. Fully understanding the matters would facilitate proper design management schemes that will reduce the cavitation problem and simultaneously extend blade life and optimal performance in the course of the flow speed changes [20].

4.5 Blade Element Momentum Theory (BEMT) with Prandtl's Tip Loss and Glauert's Correction

State the application of Blade Element Momentum Theory (BEMT) using Prandtl's Tip Loss and Glauert's correction, which increases the thrust and torque calculation accuracy. cavitation problem and simultaneously extend blade life and optimal performance in the course of the flow speed changes.

$$dT = \frac{1}{2}\rho C_T F\left(V^2 + (\omega r)^2\right) dr \quad (6)$$

$$dQ = \frac{1}{2}\rho C_Q F\left(V^2 + (\omega r)^2\right) r\, dr \quad (7)$$

where F denotes Prandtl's tip loss factor:

$$F = \frac{2}{\pi} cos^{-1}\left(e^{-f}\right), f = \frac{B}{2}\left(\frac{R-r}{r \sin \phi}\right) \quad (8)$$

In this approach, the data on efficient operation conditions is designed to be more dependable. These settings are good for displaying high-thrust conditions, among which the wake effect becomes nonlinear.

4.6 Combined Betz and Froude Theories for Efficiency

For practical efficiency modeling, the combination of the of the Betz limit and Froude's momentum theory offers a realistic perspective on energy capture for practical and efficient modeling.

$$\eta = \eta_{\text{Betz}} \cdot \eta_{\text{wake}} \cdot \eta_{\text{friction}} \quad (9)$$

where:

η_{Betz} = denotes the idealized Betz efficiency limit,

$\eta_{\text{wake}} = 1 - \delta_{\text{wake}}$ accounts for wake-induced energy loss,

$\eta_{\text{friction}} = 1 - \delta_{\text{friction}}$ represents losses due to surface friction.

This method is rather innovative; it still tends to provide theoretical limits of efficiency but takes into account practical conditions in which blades are operating to optimize their energy output.

4.7 CFD Simulation of Vortex Shedding and Wake Rotation

Rather than examining vortex shedding and wake rotation from literature studies, simulation by Computational Fluid Dynamics (CFD) with K-ε and K-ω turbulence models enables the analysis of vortex shedding and wake rotation dynamics using the Reynolds stress tensor equation as follows:

$$\frac{\partial \tau_{ij}}{\partial t} + \frac{\partial}{\partial x_k}\left(u_k \tau_{ij}\right) = P_{ij} - \epsilon_{ij} + T_{ij} \quad (10)$$

The tensor of Reynolds stress, T_{ij}, represents the Reynolds stress tensor and P_{ij} denotes production, ϵ_{ij} dissipation, and T_{ij} turbulent transport. These simulations help in identifying high-stress areas, enabling optimized blade designs that minimize vortex-induced losses and turbulence.

4.8 CFD Simulation of Vortex Shedding and Wake Rotation

For lifecycle predictions, empirical modelling of cavitation erosion and surface wear is essential. An example of an empirical wear model for cavitation-induced erosion of a blade surface is given in the following equation:

$$E = K \cdot \sigma_n \cdot (R\Delta p)^m \quad (11)$$

Where *K*, *n*, and *m* are empirically derived constants, the cavitation number, *R*, the bubble radius, and radius, and the pressure differential near the blade. This model assists in predicting blade durability, providing insights for material selection and maintenance schedules to mitigate erosion effects.

The proposed design not only offers higher accuracy but also a better cost for all the process of optimization of blades in tailored for diverse hydrodynamic and operational environments. It does so by utilizing CFD and the multivariate regression model.

The main difficulty in this type of research is to overcome the differences between geometry and fluid for the tubular turbine model testing [63]. Designing miniature prototypes, as well as executing analyses is challenging. Therefore, this CFD Analysis test of very powerful and reliable numerical simulation methods is a matter of utmost importance for the success of numerical studies. However, testing was challenging due to the complexity of instrument placement on the unit and the lack of suitable instrumentation to accurately assess the flow rate and pressure distribution in this section. Therefore, the pipe unit is simplified as a pressure pipe with upstream and downstream tanks for experimental study. Therefore, this study simplified the piping unit as a penstock with upstream and downstream tanks for experimental research, as shown in the Fig. 4. Gravity similarity criteria are used to create experimental models. Fig. 4 also shows the pattern test and measurement point layout; the geometric scale, also contains other equivalent physical size ratios. At the same time, numerical simulations were carried out for the pressure line model, considering both the free surface and water gravity

Finally, micro-tubular turbines with 9.5 cm blades are potential devices for generating electricity from low-head water sources [64]. Through continued research and development, the efficiency and performance of these turbines can be improved, making them more practical in a variety of

applications. By harnessing the power of water using micro tubular turbines, build a more sustainable, greener future.

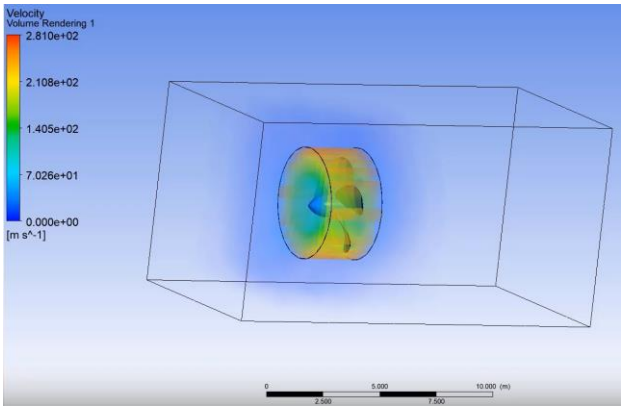

Fig. 4 Computational Fluid Dynamics (CFD) to establish the CP factor

To calculate the CP factor, which is a measure of the efficiency of the blade, use the following equation:

$$C_P = \frac{P_w}{0.5\rho A v_w^3} \quad (12)$$

Where:

C_P is the coefficient of performance

P_w is the power output in Watts

ρ is the density of the fluid (in kg/m^3)

A is the area of the blade swept by the fluid

v_w is the velocity of the fluid (in m/s)

A variety of tools and post-processing modules could be used to this end in ANSYS. Among other examples, the Monitor tool can be applied to compute the power of a blade or the Report Calculator tool will be used to find the CP factors from simulation results. All in all, the use of ANSYS Fluent is capable of blades' performance evaluation which can also be a source of guidance in the designing and optimization of these devices so that they accomplish much better efficiencies and power generation.

To analyze the flow of water and performance by the Ansys Fluent module to obtain the power and CP (Coefficient of Performance) factors on the blade: Load the blade geometry into Ansys Fluent and configure the fluid domain for simulation. Set the execution conditions for the analysis for example inlet flow rate, fluid properties, and turbulence model. Brew a mesh for flow analysis and do all the necessary modifications for accurate results. Set the analysis's boundary conditions, such as the inlet and outlet boundary conditions and wall or symmetry criteria.

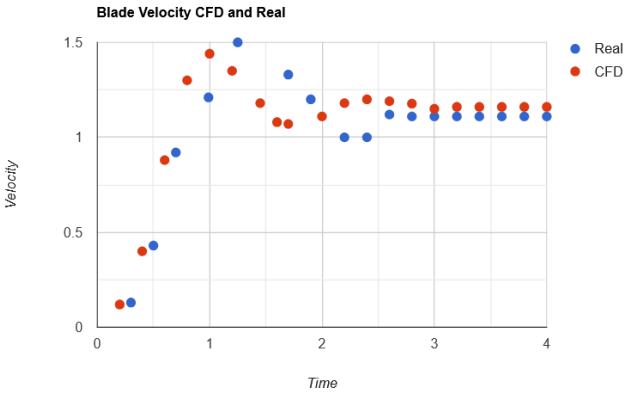

Fig. 5 Blade Velocity Computational Fluid Dynamics (CFD) and real

For Figure 5, a CFD simulation (represented by red dots) was carried out using a setup that is like the complete immersion of the blade in water at a 30-degree angle through a steady hydrodynamic environment that is close to the ideal natural flow zone. In this model, the blade is completely submerged in the water, thus allowing it to move more effectively and engage the highest velocity quite quickly and continuously without big external changes.

On the other hand, the actual real 3D setup (illustrated with blue dots) is very different. Initially, the blade is not fully submerged but at a 30-degree angle is deep in the water. The said blade is partially submerged due to the fact that there is less water resistance, and drag is also less, so it tends to get a bit higher acceleration at the beginning. Instantly after the blade starts to rotate, it gives an initial high speed. However, as it begins to get fully submerged at the same time, an upsurge in resistance occurs, which ultimately disables a deceleration mechanism to take control, and the blade keeps moving.

The differences in the initial and boundary conditions again and again confirm the contradiction between the CFD and the actual measurement. The real setup, in this case, is faster than the CFD simulation because of the only partial submersion, while the resulting chase of the car to a speed of 250 km/h and then to its rest is much more visible due to the whole blade submergence. However, the CFD model settles at a somewhat greater height because the model, in favor of simplification, assumes the

blade's gradual submersion and the real-world drag effects to be negligible in both cases.

Precisely, the required text by completing the analysis and viewing the solution convergence was achieved. The results were analyzed after the solution was validated in order to gain insight into how well the blade was working and the CP factor. Furthermore, post-processing tools and functions are provided by the Ansys Fluent module to allow post-processing and capture of these values. For instance, the Surface Integrals tool can be used to determine the total force and torque on the blade, and then they can be utilized to calculate the power and CP. The contour tool provides the fluid velocity and pressure distribution on the blade and thus can be used to describe the velocity and pressure distribution of the flow around the blade.

Micro-tubular turbines are generators that have been made on purpose small so that they can use drag force from water to create electricity. Sensitivity analysis can be performed to determine the design factors that have the greatest impact on the performance of micro-tubular turbines to maximize their performance. Streamwise and spanwise sensitivity analysis are both names of an approach that allows the sensitivity assessment of vertical and horizontal design parameters on the turbine's performance. The variation of design parameters along the length of the plate is called streamwise sensitivity analysis, while the variation of design parameters along the width of the plate is called spanwise sensitivity analysis.

The analysis of the streamwise sensitivity was done by engineers dividing the blade into sections along its length, and the design defaults are changed in each section. The effect of each parameter variation on the turbine's performance is evaluated, and the correlation of the turbine's performance with fluctuations in the design parameters is approximated. To analyse the spanwise sensitivity, engineers split the blade into sections across the entire blade width, and the design defaults were alternated in each area. The effect of each design parameter on the performance of the turbine is then examined, and performance sensitivity to the changes in the design parameters is then estimated.

Sensitivity analyzes can be performed in both streamwise and spanwise directions to identify design factors. That have the greatest impact on turbine performance and optimize micro-tubular turbine designs. One downside of micro-tubular turbines that they might become trapped in garbage or debris in the water which may reducing their efficiency and requiring maintenance. This is especially difficult in agricultural areas where the water can have a lot of dirt sometimes. When conducting a sensitivity analysis of a micro-tubular turbines blade, the following attributes must be considered: blade geometry and shape, including leading and trailing edge geometry, blade thickness, chord length, twist angle, and other design effects that affect the flow of surrounding fluids Element turbine blades. Response of a blade to stress and deformation depends on its density, Young's modulus, and Poisson's ratio.

Among flow rate, inlet velocity and pressure drop through the turbine, the effect created for the blades and the fluid flow pattern around them varies. The choice of boundary conditions like symmetry, periodicity, symmetric boundaries, in simulation, can affect the accuracy of the findings. The error of the mesh size and quality can either lead to divergence or to convergence of the simulation. By performing the fine-tuning of these parameters and scrutinizing their progress, micro-tubular turbines are likely to show their weak points and subsequently their design enhancement that leads to the effective and efficient operation is expected to be possible.

5. Result implementation

The peak flow rates observed with the tubular turbine in field ditches, where the water level sits between 1 to 1.5 m (averaging a speed of 1.11 m/s), can be linked to several factors. As the water level goes up, the flow speed tends to increase as well. This higher velocity could also be influenced by a narrowing of the ditch, which causes the water to speed up. Plus, the design of the tubular turbine itself might have played a role in achieving those peak flow rates. Its unique shape and blade setup could have been optimized for better flow, helping to hit those impressive speeds. Other things that might impact the flow rate include water temperature, the depth of the trench, and how much dirt or sediment is mixed in with the water. Moreover, dig deeper with some research and analysis to pin down exactly what's driving those peak flow rates and how they relate to changes in the environment.

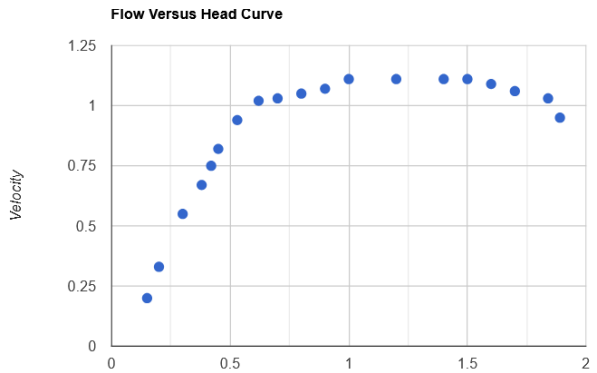

Fig. 6 Flow versus head curve in turbine mode

When the water flows at a speed that goes beyond a certain point, the turbine blades get saturated with water, which means they cannot really pull in any more energy from the flow effectively [65]. This can lead to a maximum water velocity without any boost in turbine power, as shown in Figure 6. To tackle this issue, adjust the design and spacing of the turbine blades so they can efficiently grab energy from the water flow without reaching saturation. In addition, the positioning of the turbine within the trench affects its performance, as the water flow may be unevenly distributed over the turbine blades depending on the location.

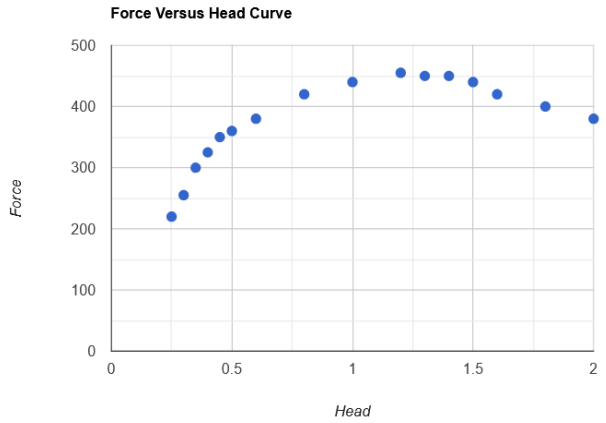

Fig. 7 Force versus head curve in turbine mode

For micro-tubular turbines, force saturation occurs when the force on the turbine blades reaches a maximum limit and no longer increases with rising water velocity. This point is typically evident on a force-head curve. In the force vs. head plot for the present case, the force peaks at approximately 450 Newtons at a water head of about 1.2 meters. Beyond this point, as water velocity continues to increase, the force on the turbine blades declines sharply as shown in Fig 7. Tests conducted in a drainage culvert, where water flows out of a partially filled circular culvert into a narrow, natural trench, provide additional insights. Due to limitations in measuring equipment, discharge (or flow rate) was not recorded, and only velocity measurements were taken. These results highlight an opportunity for further work on discharge measurement in future studies.

This behavior can be explained by the hydrodynamic principles governing turbine blade performance. At lower water flows, the turbine blades effectively capture and convert the kinetic energy of the flowing water into rotational force. However, when water velocity exceeds a certain threshold, flow separation and turbulence occur around the blades, particularly as the head level drops from the culvert into the trench. This creates unfavourable flow conditions, reducing the effective angle of attack of the blades and, consequently, the force generated.

Another contributor to performance loss is likely the limited design capacity of the turbine to harness the higher energy of fast-moving water. At elevated velocities, the turbine blades may not be optimized for such conditions, leading to reduced efficiency and diminished power output. This suggests that while the turbine is well-designed for its target speed range, its performance drops outside that optimal range.

To enhance the performance of micro-tubular turbines, the blade profile, angle, and shape should be tailored to the anticipated range of water velocities. By conducting comprehensive Computational Fluid Dynamics (CFD) simulations and extensive experimental testing, turbines can be optimized to operate effectively within the expected speed range and specific flow conditions of the drainage setup. Importantly, future designs should account for imbalances caused by erratic water movement during the rainy season, which can impact efficiency and stability.

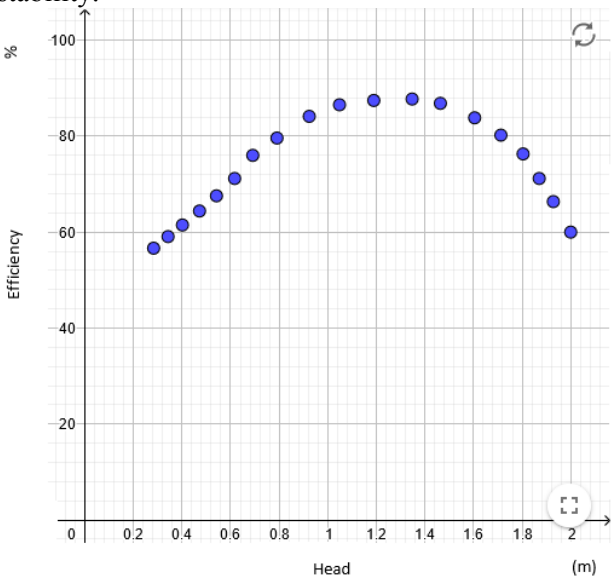

Fig. 8 Efficiency versus head curve in turbine mode

The efficiency of micro-tubular turbines is affected by many parameters, including water head (water head difference), flow rate, and the specific shape and characteristics of the turbine. It should be noted that efficiency Fig. 8 may vary depending on the specific turbine design, operating conditions and efficiency calculation technique used.

In the described scenario, the efficiency of the micro-tubular turbines peaks at around 88% at a

water head of 0.9 to 1.5 meters and then drops off rapidly. There could be a number of reasons. One possible reason is a change in the flow characteristics of the water as the water level rises. Flow patterns and water level conditions can be affected by the gradient of falling water and cause changes in turbine performance. If water levels rise, flow conditions may change and efficiency losses may occur. This can be due to changes in water speed, turbulence, or the interaction of the water flow with the turbine blades. In addition, variables such as deposits, sediment or water flow anomalies can also have an impact on turbine performance and efficiency.

Observations have shown that the springs tend to be deeper than 1.75 meters and this is only the case when there is heavy rain. Extensive experimental studies, CFD models, and field testing to identify critical components and optimize the turbine design to improve efficiency, targeting 88% under normal conditions, which was almost 97.67% during the two-year trial period (17 days below target). It is important to note that efficiency values and their variability may vary depending on turbine design, operating conditions and water supply parameters. More accurate and detailed information is needed on the efficiency of micro-tubular turbines under different operating conditions and water levels. The difference between the simulation and reality, where the water level is stagnant at 88%, rises more than falls, reduces the tendency of the micro-tubular turbines to float around turns and move against turbulence [63].

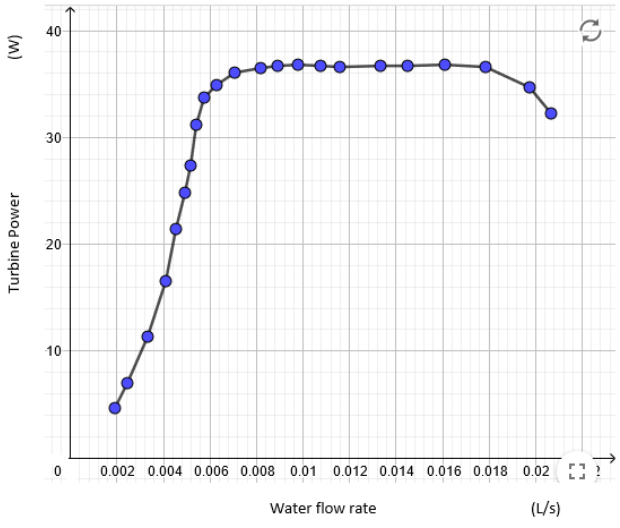

Fig. 9 Plot of power output versus flow rate

The rapid drop in turbine power at a water mass flow rate of roughly 0.018 L/s as in graph shown in Fig 9, might be caused by several factors. First, there is water cavitation. When the water flow exceeds a certain threshold, the pressure on the blade surface decreases to the point where the water evaporates and bubbles form. These air bubbles can severely loss the blade surface and reduce turbine performance. Water evaporation and foaming lead to drag losses, which affect the performance of the turbine blades, especially at high speeds (in this study, the blades were designed at an angle of maximum water velocity of 3.5 m/s). The density of the liquid decreases as the water evaporates or bubbles, resulting in a decrease in the drag force exerted on the turbine blades.

The second factor is volatility. Water on the blade surface becomes turbulent at high velocity. Turbulence causes water to separate from the blade surface, reducing the energy available in the water flow. Flow separation then occurs. The airflow can separate from the blade surface at high flow velocities, causing a pressure drop and reducing the energy that can be extracted from the airflow. To minimize losses due to turbulence, separation and drag, effective airflow control is critical. Proper blade design helps reduce aerodynamic losses and increases the overall efficiency of the turbine. Engineers can use CFD models to study different rotor blade configurations, find areas of significant turbulence or pressure gradients, and optimize the design for improved performance. Since the study targeted a considerably dominant flow of water taken from the farm, this problem with leaves was exacerbated by water overflow during the rainy season.

To a certain extent, the power of the turbine increases with the water flow. Additionally, the aforementioned factors can result in reduced power output. To improve a turbine's performance, determine the flow rate at which the power production is maximized while minimizing the negative impacts of high flow rates. When operating the generator, the user must immerse the fan of the utility generator in running water. At the beginning of the experiment, try to place the fans in ordinary streams and mountain streams. The second step is to estimate how long it will take the battery to fully charge. The last thing needed to do is make sure that the handheld generator can handle the vibrations from the spinning fan blades. This test is important to ensure the product's durability and flexibility.

One of the most novelties is the redesigned blade shape, which significantly improves energy capture efficiency. This design performs well in changing environment, particularly in places where various water levels on low side and soil erosion change. The Computational Fluid Dynamics (CFD) simulations have helped determine the best blade design for

operating conditions. This means the turbines can keep performing consistently, no matter how the flow conditions shift. Thanks to this progress, micro-tubular turbines are not only more reliable but also require less maintenance, which makes them a smart and budget-friendly option for shallow irrigation ditches. These practical benefits suggest that micro-tubular turbines have the potential to change energy access for farming communities, supporting both economic growth and the environment.

5. CONCLUSION

Research has demonstrated that micro-tubular turbines could be potential large generators of energy that run on low-head water sources like minor streams or irrigation canals. This, to a large extent, means that they can be used in areas where there is little or no electricity supply thus making them ideal for rural areas. Moreover, the use of micro-turbines may contribute to the production of renewable and clean energy. However, it should be borne in mind that their efficiency relies on which flow, water head, and turbine efficiency are the highest. It is prudent to proceed with correct (not incorrect) planning and then with installation to achieve maximum energy production and efficient performance be achieved through the use of proper planning and installation.

The U-shape tiny groove that is situated in the center of the fan blade, which was tailored specifically for hydro systems to be completely submerged in the water, has several benefits. This feature especially has the capability of blocking a larger water surface-area cross-section, hence achieving better energy harnessing from the flow. In addition, the curved groove is designed to allow the blade to capture water efficiently from multiple directions which in turn ensures that it is still able to generate the same amount of energy consistently under variable flow conditions. This attribute does not only increase the overall efficiency but also the turbine will be adaptable to various aquatic environments where water flows may be unusual.

It must be highlighted, though, that the two-year study had significant drawbacks. The effect of changes in soil structure and water pressure on the erosion of different soil type surfaces is an important constraint that requires further analysis and research as it affects the long-term performance and stability of turbine plants. The observed changes in the water thrust bedrock resulted in five-degree angle changes, underscoring the need to consider the interaction between the turbine system and the surrounding soil environment. The statement above is simply an enhancement for stationary turbine installations in specific farming areas. It is evident that the structure of the earth's surface imposes several constraints, particularly during the relocation of a moving turbine.

The above statement is only an extension of fixed turbine installations in certain agricultural areas. But so long as this turbine changes its extent fully function, the nature of the surface of the earth must be subject to innumerable limitations. Overall, tubular turbine applications have shown potential as a renewable energy option in agricultural ditches. But it's important to pay close attention to the soil's structure, erosion risk, and long-term impacts on the ecosystems in the area. This study highlights the importance of ongoing research and monitoring to maintain long-term efficient operation of tubular turbine systems in similar agricultural settings.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Khairulnizam Othman conducted the data investigation, developed the methodology, performed the simulation, created visualizations, and handled the writing.

Mohd Norzali Mohd provided mentorship external to the core team.

Muhammad Qusyairi Abdul Rahman was responsible for the conceptualization and visualization.

Mohd Hadri Mohamed Nor conducted the data investigation for the circuit module and performed simulations.

Khairulnizam Ngadimon handled the data investigation for inverters and carried out simulations.

Zulkifli Sulaiman supervised the test module employed in a practical farm setting.

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Conflict of Interest

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