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Design of a micro-hydraulic generation system based on an Archimedes screw

Diseño de un sistema de generación microhidráulica basado en un tornillo de Arquímedes

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Abstract

In this work, it is applied the principle of hydroelectric generation which is used on a large scale in Ecuador. The system built represents a didactic laboratory tool for teaching courses on renewable energies. The objective of this article is to construct a didactic hydraulic micro generator, that enables to take advantage of the kinetic energy of water to produce electrical power. In addition, to have such system available in an educational institution becomes an aid to teach concepts of renewable energies such as microhydraulics, and promote its applications in rural areas through projects related to the society. Important design aspects such as power generation, use of the Archimedes screw model, supply of water resources, cost of materials, installation of the generator, among others, have been considered. This proposal offers a low-cost educational solution that is easy to replicate, which generates a maximum power of 8(W) with a flow rate of 10(l/s), thus being able to fulfill a particular electric power demand, mainly for lighting. Through a model validated in the laboratory by means of the removable system that must be used in a real environment, tests were carried out using a water storage tank and a pump. The results enable to conclude that the system built takes advantage of a reduced water flow rate to produce clean and renewable energy.

Keywords: flow, renewables energies, microgeneration, microhydraulic, Archimedes screw

Resumen

En este trabajo se aplica el principio de generación hidroeléctrica, utilizado a gran escala en nuestro país. El sistema construido representa una herramienta didáctica de laboratorio en los cursos de docencia sobre energías renovables. El objetivo de este artículo es la construcción de un microgenerador hidráulico de carácter didáctico que permita aprovechar la energía cinética del agua para la producción de energía eléctrica. Además, disponer dicho sistema en una institución educativa ayuda a enseñar conceptos de energías renovables como la microhidráulica y potenciar sus aplicaciones en zonas rurales a través de proyectos de vinculación con la sociedad. Se han considerado aspectos de diseño importantes como potencia de generación, uso del modelo tornillo de Arquímedes, suministro del recurso hídrico, costo de materiales para la elaboración, instalación del generador, entre otros. Esta propuesta ofrece una solución didáctica de bajo costo fácil de reproducir, que genera una potencia máxima de 8 (W) con un caudal de 10 (l/s), lo que permite abastecer una determinada demanda eléctrica, principalmente de iluminación. A través de un modelo validado en laboratorio gracias al sistema desmontable que posee para ser utilizado en un entorno real, se realizaron pruebas, utilizando un tanque de almacenamiento de agua y una bomba. Con estos resultados se concluye que el sistema construido aprovecha un caudal de agua reducido para producir energía limpia y renovable.

Palabras clave: caudal, energías renovables, microgeneración, microhidráulica, tornillo de Arquímedes

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1. Introduction

The development of clean technologies for electric power generation in Ecuador has enabled to fulfill a large part of the power demand; hydroelectric generation is one of the most important nationwide, since it represents 92% of the energy matrix. However, there are certain remote places that lack a connection to the domestic electric network due to their remote location or isolation from urbanization.

The inhabitants of such rural areas do not have this basic service, and thus other types of energy, such as microhydraulics, have been used as a feasible strategy to supply the electric service. In Ecuador, this technology is within 1% together with other technologies such as biomass, biogas, geothermal, as shown in [1], which has enabled to leverage water resources at a low scale, such as streams, irrigation water or small water falls [2].

Within the field of microhydraulics, it is known that Archimedes screw is used as one of the strategies to take advantage of the flows of rivers and waterfalls. In such application it is known as hydrodynamic screw, and it consists in applying inverse engineering to the Archimedes screw, i.e., it will not operate as a rudimentary pump but more as a turbine. This system is applied at low scale to capture small water drops in rivers, waterfalls or small dams. From the technical point of view, this strategy is feasible provided that it is operated with minimum waterfalls; as opposed to those that require conventional turbines to operate, the hydrodynamic screws are high-efficiency elements regarding production of electricity for larger operating ranges, reaching a 90% with small disturbances due to changes in the flow rate. In addition, its efficiency increases according to the design volume [3].

This is the reason why, based on the available flow of water, the use of this technology facilitates the execution of this project regarding efficiency and cost, as opposed to the case that it is executed with another type of turbine, which would the efficiency and versatility of the system.

At present, hydroelectric and micro hydroelectric power generation are generally focused on the use of three turbine models, namely, Kaplan, Francis and Pelton, which, based on their structure, place of installation and efficiency [4] are among the most frequently used and studied.

The system built is based on the model developed by Archimedes, which has been used from the III century B.C., and was initially employed to raise water and other materials, i.e., as a pump [5]. Afterwards, a further change in the direction of the helixes of the screw enabled this system to be used as a turbine for power generation, as it was previously stated, taking advantage of low water jumps and flow rates, such as the one put into operation in 2012 in the Tess river dam located in England [2].

The Japanese company Sumino Co., located in the city of Ena [6], is one of the pioneers in microhydraulic systems. It has developed modules of different specifications according to the features of the installation site, which have been able to supply lighting systems in rice production places, taking advantage of the water that circulates through the irrigation channels [7].

The implementation of modules based on particular features such as the turbine structure, lengths and main elements used such as an electric generator and the water resource [8], has enabled to demonstrate various concepts such as energy transformation and the use of the hydraulic potential in places where it is difficult to access to electric power, which poses a challenge regarding technological innovation to address this type of problems.

Based on the above, the main objective is the implementation of a microhydraulic generation didactic system based on a hydrodynamic screw, to supply one or more lighting loads using a reduced flow of a water resource.

Despite the advantages offered by the use of this technology with hydrodynamic screws, if it is chosen as an economically feasible alternative to be used in the long term in rural areas, it is compulsory, due to environmental care issues, to measure the impact on the incorporation rate of oxygen to the river, which should be preserved. Therefore, it is a topic of study to add a corrective or preventive strategy when using this technology; indeed, there is very little said and researched about assessing if there is a significant impact on rivers and lagoons, as well as on marine fauna [9].

2. State of the art

Santa Cruz [10] carried the study and design of a micro hydroelectric system to supply electric power to a household in Cuenca. This study stated that Archimedes screw is the best alternative for small water jumps and low flow rates; however, a Kaplan turbine was used because this locality had high flows.

Ramírez and Ramón [11] conducted a preliminary study for the implementation of a hydroelectric microgeneration system for self-supply of a hostel in the Ecuadorian Amazon. They found that it was feasible to install a 7.5 (kW) turbogenerator that takes advantage of the water of various internal waterfalls that exist due to the Reventador river crossing; a group of Pelton-type turbines were chosen because the water resource is abundant in the area. Nevertheless, they point out that for powers below 300 (W) and flow rates below 50 (l/s), it is recommended to use hydrodynamic screws.

Arias [12] conducted a feasibility study of a hydroelectric microgeneration system using Kaplan turbines, pointing out the initial investment and the benefits for communities that do not have a high population growth and are at distances smaller than 500 meters from the power supply point. In addition, this study states the importance of implementing low-cost microhydraulic systems to supply the power demand of particular lighting loads, and shows that hydrodynamic screws are an excellent alternative.

Lucio [13] carried out the construction of an Archimedes screw mini turbine, where it is shown the optimal operation of the system in an irrigation channel, obtaining power and torque levels that are appropriate to generate mechanical power (it does not supply electric loads).

All the studies described above show the importance of microhydraulics in Ecuador and its applications; nevertheless, none of them presents the design and implementation of a cost-effective electric microgeneration system based on hydrodynamic screws for self-supply at places that have small water jumps and low flow rates, and are isolated from the electric network. Although the system built has academic purposes, it is intended to formulate projects related to the society to repower it for its use at isolated places. In addition, this work contains all the technical information for the implementation of the microturbine and its application, showing the contribution of this paper in the area of renewable energies.

Table 1 gathers some papers that analyze the parameters, operation, modelling, etc. of microhydraulic systems that use Archimedes screw generators. These papers remark the efficiency of these turbines to generate hydroelectricity at places with little height and moderate flow rate.

Table 1. Similar papers about Archimedes screw generators

Paper	**Feature analyzed**
[14]	Performance
[15]	Slope and number of blades
[16]	Power
[17]	Size
[18]	Types of fluids

Simmons *et al.* [19] analyzed Archimedes screw generators for sustainable energy development, generating hydroelectric energy in plants of up to 200 (kW). In addition, they state that this type of technology can be used for rural electrification in developing regions with reliable little water resources. Raza *et al..*. [20] remark that the electricity generated using hydraulic energy is cheaper and environmentally friendly; in addition, they state that microgeneration systems not connected to the network may use waste water, and that Archimedes turbine is the most appropriate one for a hydroelectric plant with a low waterfall.

The objective of this research is to develop a cost-effective and easy to replicate didactic system, to disseminate the knowledge in the area of microhydraulics, generating clean and renewable energy. Low-cot materials were used for the construction of the microturbine. The energy generated enabled to supply lighting loads using low water flow rates, thus validating the operation of the system developed. The system put into operation in this research work may be repowered to supplement and lower costs in projects [10–13]. In addition, it may be used in a didactic manner in university labs to motivate students to study and become experts in the area of renewable energies, to contribute to the change of the energy matrix in Ecuador.

3. Materials and methods

This section presents the development stages of the project, describing the materials and methods employed. The system proposed may be divided into two parts:

1. Mechanical design
2. Electric-electronic system

3.1. Mechanical design

3.1.1. Power of an Archimedes screw turbine

In the case of a hydraulic turbine, the power is governed by variables defined by the place where it will be installed, such as the inlet flow rate, the height, and also aspects such as water density and gravity. Equation (1) establishes the parameters to be included to obtain the hydraulic power of a turbine [21].

$$P_H = \rho \times g \times Q \times H \tag{1}$$

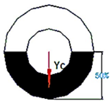
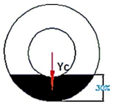
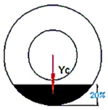
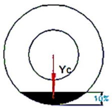
Where P_H is the hydraulic power in (W), ρ corresponds to the water density in (kg/m^3), g is the gravity on earth in (m/s^2), Q is the flow rate that enters the turbine in (m^3/s), and H is the height of the waterfall in (m).

3.1.2. Inertia and area of the helix

Table 2 considers the inertia of the turbine as a function of the contact area. A minimum area is contemplated for this design; specifically, a 10 % is considered since the inlet area of the recirculation water is smaller than one inch.

Considering the equations for such 10 %, it is obtained that A is the area of contact of the water with the helixes of the turbine in (m^2), R is the external radius of the turbine in (m) and Y_c is the inertia of the blade in (m) depending on the area of contact to be chosen [21].

Table 2. Inertia of the turbine as a function of the percentage of the contact area [21]

Area of contact	Area (A)	Percentage	Inertia (Yc)
	$\frac{3}{8} \times \pi \times R^2$	50%	$0.4951 \times R$
	$\frac{9}{40} \times \pi \times R^2$	30%	$0.6907 \times R$
	$\frac{3}{20} \times \pi \times R^2$	20%	$0.7544 \times R$
	$\frac{3}{40} \times \pi \times R^2$	10%	$0.8471 \times R$

3.1.3. Theoretical torque and power

Figure 1 shows the horizontal thrust force exerted by the water (F_X), the tangential force exerted by the water (F_Z), the thrust force in the direction of the X plane (F_R), the force exerted by the water on the housing (F_y), the vertical force (W) and (α) the angle external to the helix [21].

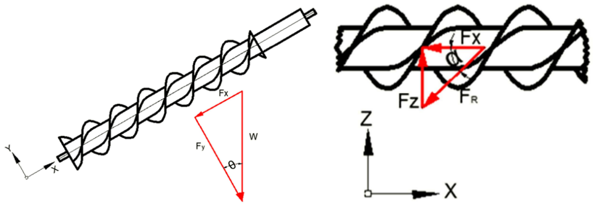


Figure 1. Forces that act on an Archimedes screw [21]

If the relationship between the XZ plane is considered, the relationship given by equation (2) may be obtained.

$$tan\alpha = \frac{F_Z}{F_X} \tag{2}$$

Where the tangential force (F_z) together with the inertia of the blade (Y_C), describe the torque generated at the moment of contact of the water with the screw, thus obtaining equation (3).

$$T = F_Z \times Y_C \tag{3}$$

Equation (4) may be obtained analyzing the tangential force (F_Z); this equation describes the torque of the screw considering the effects of the water, the height, the contact area and the angles.

$$T = \rho \times g \times LT \times A \times sen\ (\Theta) \times tan\ (\alpha) \times Y_C \tag{4}$$

Where T is the torque of the turbine in (Nm), ρ is the water density in (kg/m^3), LT is the total length of the turbine in (m), whose value is assumed based on technical criteria of design, materials, manufacturing feasibility and versatility, Θ is the inclination angle of the turbine in (°) and h is the height of the hydraulic head; LT, Θ and h are shown in Figure 2.

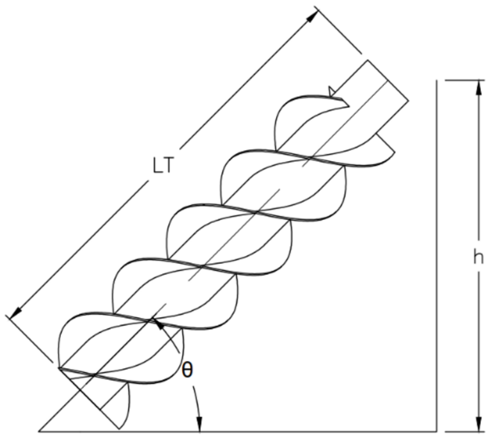


Figure 2. Dimensions considered for the turbine

On the other hand, the theoretical mechanical power of an Archimedes screw may be also expressed as shown in equation (5).

$$P_{theoretical} = T \times \omega \tag{5}$$

Where T is the torque obtained from equation (4), and ω is the angular speed in (rad/s) given by equation (6).

$$\omega_{angular} = \frac{Q \times tan(\alpha)}{A \times Y_h} \tag{6}$$

Substitution of equations (4) and (6) in equation (5) yields equation (7), which describes not only standard variables as in equation (1), but is also makes emphasis on the contact area, inertia, angles and lengths.

$$P_{theoretical} = \rho \times g \times LT \times A \times Q \times sen(\Theta) \tan^2(\Theta) \tag{7}$$

In order to obtain the angle α, it is considered that the efficiency should be assumed in this case due to various factors such as friction, weight of the turbine, the environment, etc. Hence, equation (8) gives the efficiency of a turbine.

$$\eta = \frac{P_{theoretical}}{P_{theoretical\_max}} \times 100\% \tag{8}$$

Where η is the efficiency of a turbine and $P_{theoretical\_max}$ is the maximum mechanical power that can be reached by the turbine in (W). Simplifying equation (7) and substituting the result in both variables of equation (8) yields equation (9), where it can be observed that $\tan^2(\alpha)$ is 1 in the numerator because the maximum angle α should be 45°.

$$\eta = \frac{\rho \times g \times LT \times A \times Q \times sin(\Theta)\tan^2(\alpha)}{\rho \times g \times h \times Q} \times 100\% \tag{9}$$

From Figure 2 it is determined that the height is given by equation (10):

$$H = LT \times sin(\Theta) \tag{10}$$

Considering equation (10) and substituting and simplifying equation (9) results in equation (11), which can be used to determine the value of the external angle (α):

$$\eta = \tan^{\alpha} \times 100\ \% \tag{11}$$

The theoretical torque and power that may be obtained from an Archimedes screw turbine can be found using equations (4) and (7).

3.1.4. Dimensions and modeling

It was adapted an Archimedes screw with three threads and two revolutions along a plastic shaft with a length of 0.76 (m), according to the base design taken as reference. This piece was divided into two sections that may be coupled. Figure 3 shows the Archimedes screw; it does not have a solid filling and has a thickness of 0.003 (m) in its shaft and a thickness of 0.002 (m) in its helixes. In the lateral end it has a hole to attach the turbine with respect to a metallic shaft.

Figure 3. Archimedes screw hydraulic microturbine

A prototype of the existing microgeneration turbine was taken into account for the design of the microturbine. The corresponding geometrical specifications were adapted to the proposed design, and such features are specified in Table 3.

Table 3. Features of the hydraulic microturbine

Property	Value
Material	Ácido poliláctico
Length	0.760 (m)
External diameter of the helix	0.198 (m)
Diameter of the helix shaft	0.109 (m)
Thickness	0.003 (m)

Measures to prevent friction in rotating parts include maintaining the bearings lubricated and protecting the metallic parts from rust, since in Archimedes screws it is of vital importance to avoid friction, especially in the helical helixes, because of efficiency issues [22].

A metallic structure, with the dimensions shown in Table 4, was designed to fix the bearings that bear the microturbine. This structure is the support of the water stream channel and the microturbine, and also holds the generator and the electronic circuit. Such structure is associated to auxiliary mounts that define the inclination and equilibrium of the surface on which the entire turbine-generator system will be deployed.

Table 4. Features of the hydraulic microturbine

Property	Valor
Width	0,81 (m)
Length	0,281 (m)
Height	0,221 (m)

Once the purpose of the base metallic structure has been defined, the plane of its final design is obtained (Figure 4).

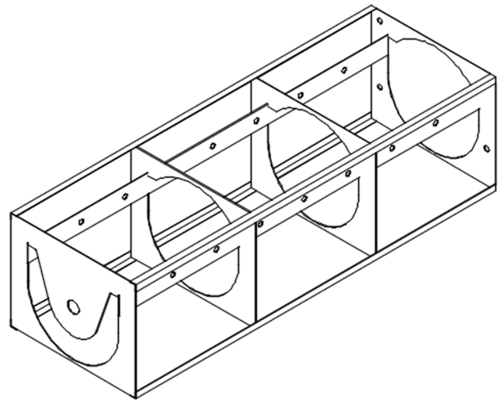


Figure 4. Support base of the hydraulic screw

Figure 5 shows the 3D model of the microturbine. An insulated container is placed in the back of the metallic structure to hold the generator and the electronic circuit. In addition, it can be observed the auxiliary metallic structures to set the inclination of the hydraulic turbine, and even fix the hydraulic pump and the water storage tank for laboratory tests. Such structures may be removed for operation in a stream or creek.

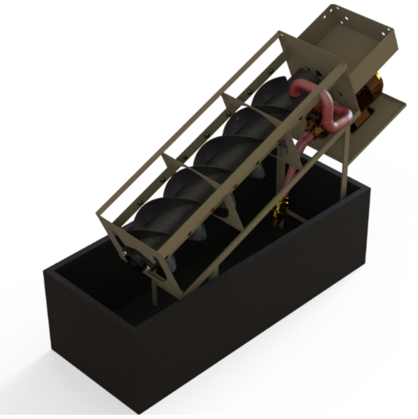


Figure 5. Rendered design of the microgeneration system

3.2. Electric-electronic system

A water recirculation system was used for the laboratory tests, and thus a storage tank was arranged to receive and discharge the fluid by means of a 372.85 (W) hydraulic pump.

A brushless DC motor (BLDC), whose main parts are shown in Figure 6, was used to produce electricity. This BLDC is operated as a generator without velocity multipliers, and is coupled to the back of Archimedes screw. This element adapts to the revolutions by means of a direct mechanical coupling provided by the turbine; in addition, the inclination of Archimedes screw and the flow rate that enters the turbine through the helixes have influence on the conversion from mechanical energy to electrical energy.

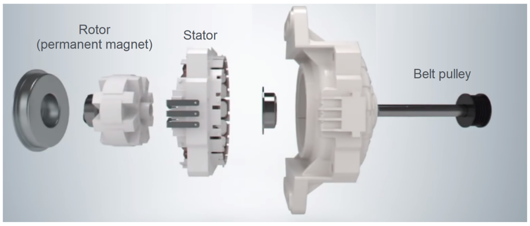


Figure 6. Permanent magnet synchronous motor [23]

It was designed the electronic circuit for the voltage rectifier circuit that will supply the loads. This circuit has stages for rectifying, filtering and linearizing the alternate voltage wave at the output of the generator. In addition, a step-up DC–DC booster converter (MT3608) was incorporated to regulate and amplify the filtered DC voltage waves. The electronic scheme is shown in Figure 7.

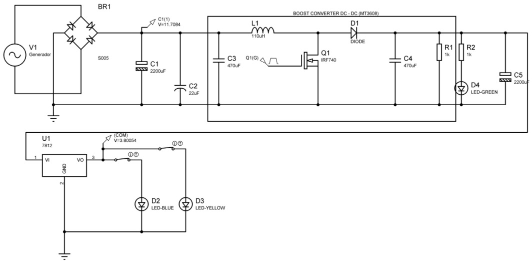


Figure 7. Electronic scheme of the full-wave AC-DC voltage rectifier

4. Results and discussion

Taking into account all the parameters, features and requirements of the hydraulic microgeneration technology, a cost-effective and easy to replicate didactic system was built capable of using a water resource to generate up to 8 (W), supplying the demand of 6 (V) LED lighting loads. The system may be easily disassembled for its transportation from one place to another when it is required to observe its operation, either in the laboratory or outdoors. In addition, the system designed and built represents an innovative and efficient solution that may be improved for generating electricity from unconventional renewable sources.

The hydraulic screw was made through 3D printing (Figure 8) in fused deposition modeling (MDF), using polylactic acid filament in the entire structure of the hydraulic microturbine.

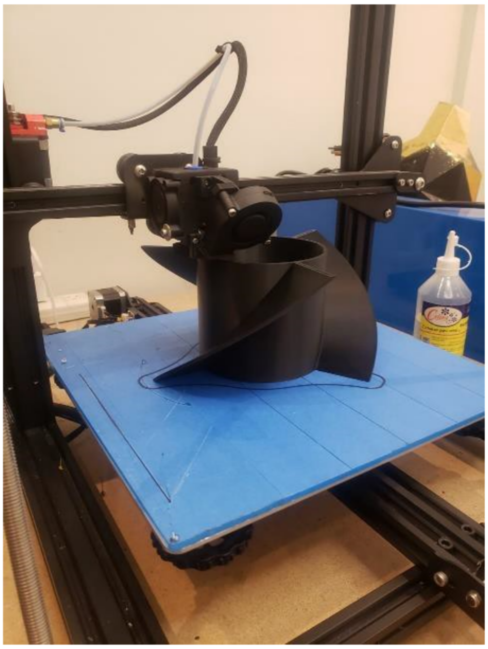


Figure 8. Metallic structure that supports the microgeneration system

Figure 9shows the system built and operating in the laboratory, the demand (6V LED lights) is satisfactorily supplied using to the inlet flow of water that is recirculating through the system.

Figure 9. Metallic structure that supports the microgeneration system

En la Figura 10 se observa el sistema construido y funcionando en laboratorio, la demanda establecida (luces LED de 6 V) es abastecida correctamente gracias al flujo de agua de entrada que se encuentra recirculando por el sistema.

Si bien el sistema de microgeneración cuenta con una bomba de agua para un circuito hidráulico que recircula el agua, esto sirve para emular el medio físico donde se instalaría dicho sistema y realizar las respectivas pruebas de funcionamiento en laboratorio. Para la adaptación y utilización del sistema en lugares externos al laboratorio no son necesarios estos componentes por lo cual se pueden desmontar fácilmente, ya que lo único que se necesita es la presencia de un riachuelo y la colocación del generador para el paso de agua (Figura 11).

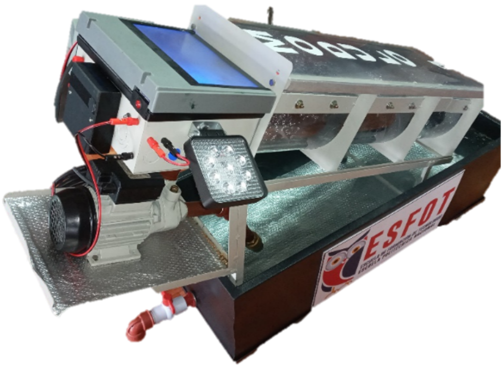


Figure 10. Hydraulic microgeneration system

As a constant flow rate (minimum) of 0.583 (l/s) enters the turbine, it rotates at a speed in the range from 18.85 to 20.94 (rad/s) with the corresponding coupling to the generator. As a flow rate (maximum) of 10 (l/s) enters the turbine, it rotates at a speed of approximately 220 (rad/s).

Figure 11. Microhydraulic generation system installed in a stream

Tests were carried out for different inlet flow rates, measuring the power generated to supply a particular load. Table 5 and Figure 12 show the power generated by the microturbine built in this work, as a function of the inlet flow rate.

The power generated was established through operation tests, which show that as the inlet flow rate increases so does the power. With the minimum flow rate of 0.583 (l/s), a current of 0.4 (A) and a voltage of 6 (V) were obtained, which can be used to supply a LED light with these specifications, whereas the maximum flow rate enables supplying up to 3 LED lights. Although there are various systems to supply the power demand without connecting to the electric network, even obtaining higher levels of power, the microturbine built represents a very attractive alternative for school students to get involved in the area of microhydraulics. This type of technology is capable of recovering the energy from a great variety of small water jumps, and its installation and maintenance costs are very low compared to other renewable energies.

The system presented in this work is feasible because it uses low-cost materials; in addition, the technical information presented in this paper constitutes a basis to build, replicate and repower a system, that can also adapt to different environments, indoors or outdoors.

These results evidence that the objective of the microgeneration didactic system was fulfilled, which is to contribute to the development of students' knowledge about renewable energies, by means of the supply of the demand of lighting loads from the kinetic energy of water. Figure 13 shows the training of students from the Escuela de Formación de Tecnólogos (ESFOT) of the Escuela Politécnica Nacional, in the operation of the system.

Table 5. Values of power generated as a function of the inlet flow rate

Inlet flow rate (l/s)	Power generated (W)
0.583	0.57
1.243	0.93
1.846	1.24
2.394	1.38
2.749	1.47
3.198	1.78
3.639	2.16
4.957	2.78
5.293	3.11
5.384	3.21
6.393	4.09
7.475	5.28
8.273	6.14
9.583	7.32
10	7.95

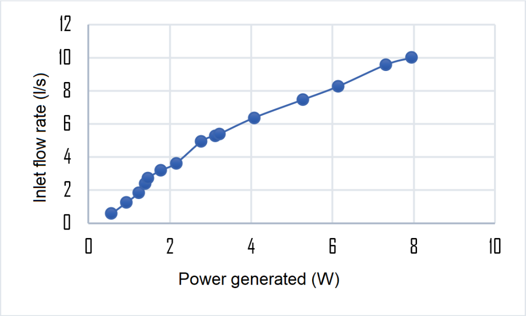


Figure 12. Power generated by the microturbine vs. inlet flow rate

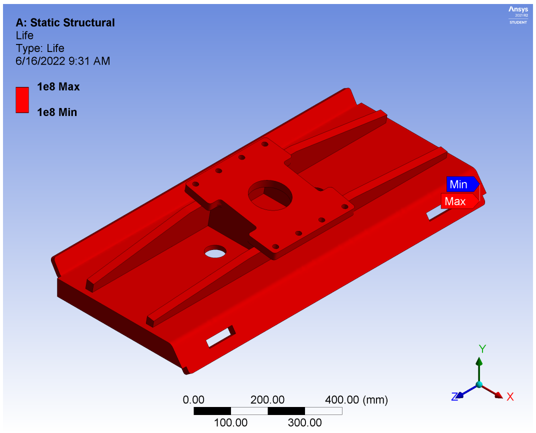


Figure 13. Students observing the operation of the microgeneration system in the laboratory

The installation of a rectifier was considered to supply the lighting load, in order to avoid the intermittency in the lamp used and to stabilize the power delivered by the generator.

Consequently, based on the microturbine design specifications, there are losses due to different factors, such as the friction, resistance of the generator, weight, etc., which cause losses in the stage of transformation from mechanical to electrical energy. Nevertheless, hydrodynamic screws exhibit high efficiency regarding generation of electricity for larger operating ranges, reaching 90% with little disturbances in the flow rate; in addition, its efficiency increases according to the design volume.

The system built is a contribution to the development of knowledge about microhydraulics, since the results obtained enable to verify that the module operates correctly and that it may be used for teaching activities in laboratory practices. In addition, it should be pointed out that the operation tests have been carried out with the system to recirculate the water (pumps, pipes and storage tank) in the ESFOT laboratory and in a stream in the locality of Guayllabamba, being able to satisfactorily supply lighting loads. Therefore, it is stated that the didactic microturbine implemented in this work may serve as a base to extend the system to real applications in areas isolated from the electric network, taking into account the demand that should be fulfilled.

An aspect that should be considered is the energy storage system that would be used by the lighting load during dry seasons; however, a continuous and stable presence of the water resource has been considered for the present project, i.e., it is used the energy produced when the system is operated.

5. Conclusions

Based on the values obtained and on the implementation of the microgeneration system, it is emphasized that the water flow is the resource used to produce movement, as it was verified in the tests carried out with a water flow rate of 0.583 (l/s), in which the screw moved at a considerable speed. However, a higher efficiency is obtained when the flow rate is increased, generating better torque and a power of up to 8 (W) to supply a larger number of loads connected.

The microgeneration system based on an Archimedes screw enables to supply up to three LED lights of 6 (V) and 0.4 (A). Although it is a didactic system, it could be improved and its performance extended to supply a larger demand.

The turbine was thoroughly calibrated and adjusted, so that there is no direct contact of the turbine with the metallic structure and also to guarantee that it is as centered as possible at the moment of starting operation. The dimensions of the general system were defined and mechanical design planes were made for the corresponding description.

Taking into account the electric demand to be supplied and the technical information of the present paper, the system built may be repowered to increase the generation levels through a generator of higher power. This will enable to use the microturbine in lighting systems, in passages and streets without a public lighting system, for electrifying fences to protect crops and cattle, and even in irrigation systems in rural areas of Ecuador.

In the present work, a system based on clean and renewable energy was designed and built. Low-cost materials were used to obtain a cost-effective and easy to replicate system, and also easy to repower compared to other types of technologies.

The system built is a contribution for the microhydraulic technology and its socialization in educational institutions, so that students and other people interested may know and learn about this type of technology. In the case of the ESFOT, the microturbine can be used for didactic applications in the laboratory, where students may extend, strengthen and supplement their knowledge related to renewable energies. In addition, this work is framed within the area of Applied Technology projects at the ESFOT, which have enabled to state technical solutions in different projects that involve a relationship with the society.

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