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Study of a Low-Tech Rain Water-Powered Triboelectric Generator as a Renewable Energy

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Abstract— This article aims to determine an efficient way to create a low-tech rain-powered triboelectric generator. The harvester can be useful to power some low power devices (sensors, lights, IoT...) or to compensate for other energy sources in building for example. For this purpose, a fluid flow triboelectricity is studied. So, a setup that aims to measure the energy possibly gathered was built, and optimized as much as possible with recycled materials. A great work was made on pipe optimization concerning dimensions, electrodes position, resonances and embedding. The setup was also improved to spend the least water since it is the limiting factor. For the flow rate influence was studied and the results were summarized on an efficiency graph. Then, the impact of triboelectricity and the ways to make it more efficient were reviewed by considering material optimization, surface charge managing, placement. Thus, the magnitude of recoverable energy was evaluated to determine the best way to build the generator. Finally, the generator was built to prove its feasibility and offer an electric voltage in open circuit of 100mV to 600mV.

Keywords— Affordable electricity generator, Water flow triboelectricity (WFT), Plastic pipe recycling, Experimentation.

I. INTRODUCTION

The progress of ubiquitous nomad electronic devices such as communication node (IoT, IIoT, ...), lighting systems (LED, LED tape,...), sensors (temperature, pressure, ...) or some actuators (electronic relay, electric motors, stepper motors, jackscrews, ...) requires the guarantee on energy consumption autonomy. The solution of self-powered devices is expected, and researchers are working on the design and development of low energy self-powered electronic devices [1]. So far, nano and micro self-powered generators based on acoustic vibrations [2] were featured by using for example

MEMS technology [3,4]. Improved energy harvesters using non-linear [5] and ultrasonic [6,7] techniques were proposed for wideband vibrations. However, vibration-based energy harvesters are particularly expensive and limited to specific environment sources. For this reason, we would investigate lower-cost harvesters using water triboelectric ambient energy [8-11].

Water energy harvesting is an innovative technology for the future electronic autonomous devices [12-14]. Since this last decade, several types of triboelectric nanogenerators (TENG) [15-19] are invented that is used to convert mechanical energy into electricity by a conjunction of triboelectrification and electrostatic induction. The triboelectricity of water has become a hot research topic since the last decade [15-21]. In the present work, the case of rainwater flowing in the pipe is studied [15,20,21]. It consists of mechanically extracting electrons by a flow of water and providing a potential difference between the beginning and the end of the pipe. Thus, a voltage is generated using this potential difference [15,20].

The triboelectric effect of water was initially an open question [22]. Triboelectricity is an electrostatic phenomenon created by the contact of two materials of different nature [22]. The triboelectrification is an effect probably known since ancient Greek time, but it is usually taken as a negative effect, and avoided in many technologies. It occurs when a part of the electrons of the contact surface of one of the two materials is transferred to the other and this transfer remains during the separation [14,22]. Different chemical investigations with tribochemistry were performed to understand the fundamental mechanism of the interface interaction [23,24]. The triboelectric effect can be increased by adding mechanical energy. In this case, the materials are rubbed against each other, and it is called “friction” [21,22]. The tactic, reactive, and functional droplets are studied [25]. The possibility of wave energy conversion in function of the nanostructured solid/liquid interface was experimented [19,26]. Different

empirical studies confirm the feasibility of energy harvesting especially with triboelectric generators [9-13]. It is important to note that the water energy harvesting is promising notably for all fabric [16], service behavior [17] and stick compact structure [9].

The basic idea of the present research work is to exploit rainwater to design an affordable triboelectric generator (TEG). It acts as a particular way of gathering energy using triboelectricity by friction with a fluid flow. As depicted by Fig. 1, the self-power system using waterfall triboelectricity (WFT) can be implemented by gathering rain in an elevated tank and let it fall into pipes where triboelectricity phenomenon appears. Our goal is to develop water fall triboelectricity (WFT) as a pioneer self-power solution of easy to build anywhere on the earth. The storage of water in a tank is guaranteed by the rainfall as assessed based on high-temporal resolution records [27,28]. Under tropics, the rainfall season can last up to six months [29,30]. The precipitations in certain countries [31,32] represent a high amount of unused potential energy that the present research work aims to exploit. In the future, water triboelectricity can be combined in hybrid system for example with sunlight, raindrops, and wind renewable sources [33,34].

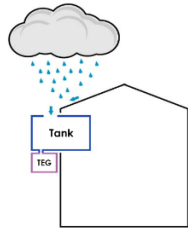


Fig. 1. WFT potential placement for a house environment.

For this purpose, we will examine different ways of producing triboelectricity energy by determining the gathered energy magnitude, and considering the feasibility and the cost. The influence of exterior parameters will help optimize the TEG to make as much as possible with limited means. We will focus on improving a given experimental setup by varying different parameters to prove the viability of such a part of a water pipe generator (WPG). WPG will be first one WFT and thereafter a combinaison of WFT.

The contributions of the present study are: the WFT for the WPG understanding for a simple way implementation to be innovative, ecologic and affordable energy production technique by recycling objects (here pipe, bottle and copper), the characterization and the measurement of the voltage gain for an open circuit and thus the estimation of potential energy in reserve, and to finish, the characterization and the measurement of the voltage gain for a closed-circuit with a load impedance, and thus the potential energy in use.

The rest of the article is organized into five sections. The WFT understanding principle with experimental setup is presented in section 2. The influence of the pipe length, on the probe position (inner/outer), on the flow rate, and on the temperature are shown in subsections. In section3, the optimization approach of the WPG is elaborated by studying the impact of an additional probe and by two-pipe embedding. In section 4, a low-tech WPG with recycling material was created with height single plastic pipes, exterior probes, 1,5l plastic bottle. We plug the WFT in serial or parallel to combine and optimize the output power, respectively, in order to obtain a better WPG. Then conclusion is done in section 5.

II. EXPERIMENTATION PRINCIPLE OF THE WFT GENERATOR

The operation principle of the WFT generator is described in the present section. Experimental setup is presented first, then influence of the pipe length, of the probe position (inner/outer), of the flow rate, and the temperature are shown.

A. WFT experimental setup

To design a WFT generator, a simple metal probe is used. Two cases are investigated depending on the inner and outer probe positions. First, the electrodes, as copper conductive wires, are placed inside, in contact with the pipe and the water. Then, the electrodes as iron rings, are placed outside only in contact with the pipe. As reported by Fig. 2(a), the experimentation uses a syringe linked to a pipe of which both ends are connected to copper electrodes and a multimeter.

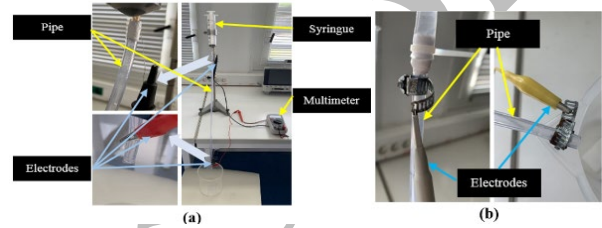


Fig. 2. Experimental setups of (a) syringe-pipe and (b) electrode installation.

Then, the electrodes are placed outside the pipe, as illustrated by Fig. 2(b), and iron rings are used in this case. Only the potential difference between the two ends of the pipe (of which electrons were snatched) is measured. We underline that the charge flow in the water has no influence on this measure. Moreover, the cables were shielded against electromagnetic pollution. Finally, different inclinations as 25°, 45° and 70° from the vertical axis of the pipe were considered. The output voltage was not modified significantly enough to consider this factor around $V_{out}=3$ mV at most. Thus, the vertical position was chosen for the pipe.

B. Influence of the pipe length and the probe position

The influence of the pipe on the electricity generated by the WFT is investigated in the present subsection.

1) Inner probe scenario and optimization of the length pipe

To gather as much energy as possible and to have a reasonable sized WPG, a compromise must be found between the pipe length and diameter. This first set of experiments aims to find the most efficient length. A 60 mL syringe was filled with water and emptied at a constant flow rate. The syringe is emptied in 10 seconds at constant speed in different length pipes, with a 4 mm diameter. The potential difference between the ends of the pipe is reported in Fig. 3. A highly non-linear influence of the pipe length should be noticed. This influence is also due to the difficulties of the experimentation since the mouthpiece of the syringe has a smaller diameter than the pipe. Consequently, a sort of cavitation effect took place in the pipe, that had to be solved by slightly bending the beginning of the pipe and making the surface variation smoother with Teflon®. Moreover small-sized pipes shorter than 10 cm, seem to have an unstable distribution of charges which makes the potential difference fluctuate in a random manner, these sizes will be explored with a better setup. An optimum can be acknowledged for a 35 cm long pipe, this effect will be analyzed afterwards. The diameter of the pipe can also be influential, to determine its ideal size it must be acknowledged

that in the actual WPG, a gravity flow will be the engine, thus too small of a diameter would be an issue since superficial electro-motive forces and friction due to viscosity would slow down the flow and then reduce power as demonstrated afterwards.

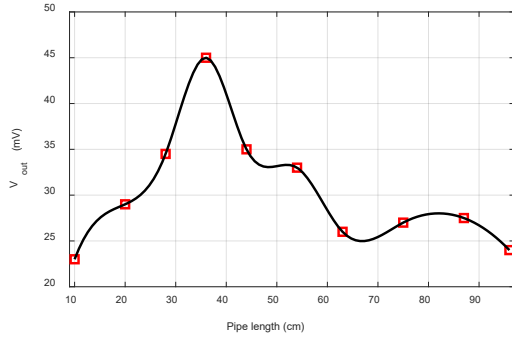


Fig. 3. WPG output voltage with inner probe vs pipe length.

However, smaller diameter pipes have a better efficiency (power for a given flow rate) as experiences have shown (a 1 mm diameter pipe is 1.6 times more efficient than a 4 mm one which is itself 2.0 times more efficient than a 10 mm diameter pipe). Thus, the chosen compromise was the 4 mm pipe that will be kept throughout all the experimentation. It should also be noted that we tried enhancing the efficiency of the setup by inserting small wires of different materials inside the pipe (such as different types of plastic, metal...) so more electrons could be snatched, but the voltage magnitude did not change, or not significantly enough to be measured.

2) Outer probe scenario and optimization of the length pipe

In this case, the influence of the pipe diameter is examined with the outer probes. The results are revealed by Fig. 4(a). It should be noted that for this experiment, sliding the exterior electrode on the pipe snatches electrons and makes the potential variation of about few seconds, so there was a 30 seconds “resting time” taken before every measure.

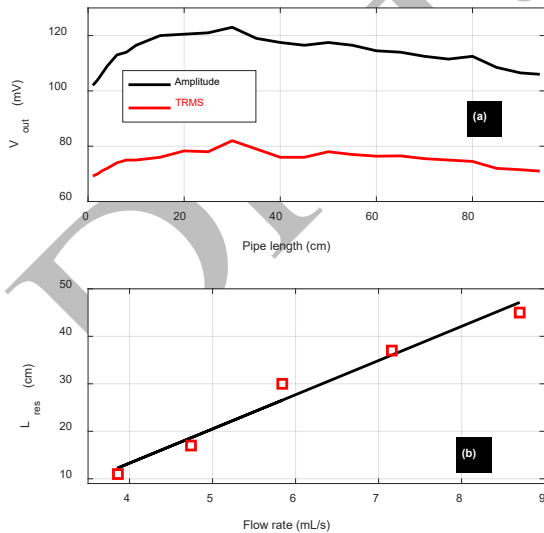


Fig. 4. (a) Pipe length optimization with outer probe and (b) resonance lengths vs flow rate.

The curve and its optimum observed for a 30 cm long pipe are really like the ones with interior electrodes. Then, it can then be thought that the flow of charges inside the pipe and the

potential difference outside the pipe are linked. In fact, the snatched electrons are mainly (maybe even only) the ones of the pipe. The empirical linear regression fitted model of resonance length is given with Excel® :

$$L_{res}(Q)=7.2Q-15.5 \text{ (cm)} \quad (1)$$

was indeed observed for every flow rate Q (in mL/s) in our range of measurements. The pipe length is from 10 cm to 50 cm and results are reported in Fig. 4(b). This will be useful for an actual WPG where the range of flow rates is determined by the tank height. We could conclude that the choice of the pipe length to put the probes and the flow rate are related to give the maximum voltage output. Then for long pipe, for a flow rate at 6 mL/s, it could be added some probes every 30 cm to obtain a maximum output voltage.

C. Flow rate influence

In this subsection, the previous setup was improved to have stable voltage measurements and to be able to vary the flow rate. In this stake, it was added an electrical pump of which the flow rate can be controlled thanks to the generator as seen in Fig. 5. The results are discussed in the following paragraphs.

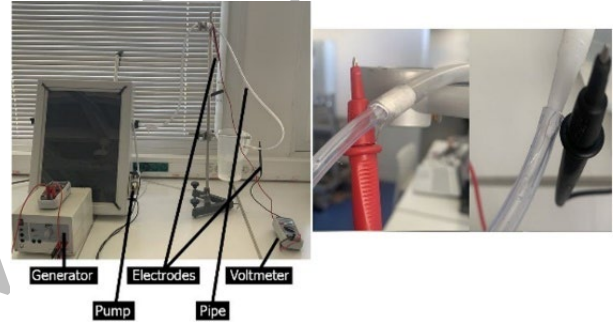


Fig. 5. Experimental setup with an added pump.

1) Inner probe scenario versus flow rate

Fig. 6 displays the influence of the flow rate on the output voltage with inner probe. The coefficients differ though, this might be due to the fact that the experiment was carried out with different materials.

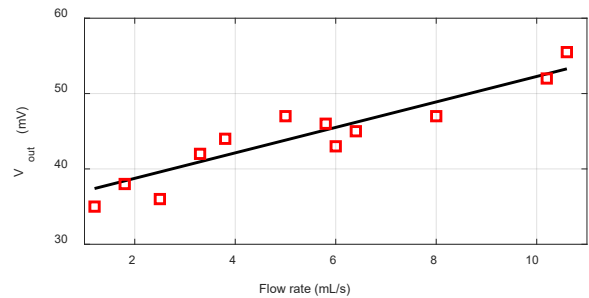


Fig. 6. WPG output voltage with inner probe vs flow rate.

But most importantly the range of flow rates examined was really different. This study focused on low flow rates that are in the magnitude of a gravity flow. In such a range, it can be seen that the experimental points do not precisely fit with the curve.

2) Outer probe scenario versus flow rate

Fig. 7 shows the influence of the flow rate on the output voltage with an outer electrode. Unlike in previous subsection, the linear regression fitted output voltage:

$V_{out}(Q)=-2.13Q+165.75$ (mV) (2)
decreases when the flow rate Q (in mL/s) increases.

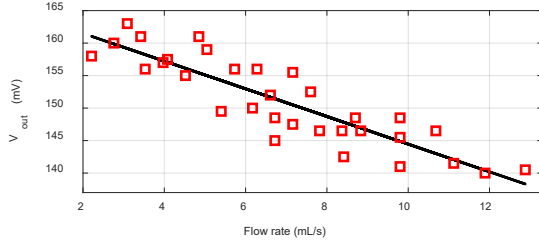


Fig. 7. WPG output voltage with outer probe vs flow rate.

This voltage variation was not predictable since a higher Q is expected to snatch more electrons to the pipe. Furthermore, these measurements are not to be doubted since the experiment was carried out multiple times with always a negative slope in result.

D. Temperature influence

The position of the WPG is also at stake. It might have to be facing or hidden from the sun and painted in specific colors. This is why was examined the influence of the environment's temperature. To this end, the pipe was heated thanks to a high-power lamp from different distances as shown in Fig. 5. Each measurement was realized with a thermal probe after thermal equilibrium is reached. The experiment was carried out with inner and outer probe. In every case, as depicted by Figs. 8(a) and 8(b), the measurements show the importance of putting the WPG in an enlightened environment and even painting it in black so it can absorb more radiations.

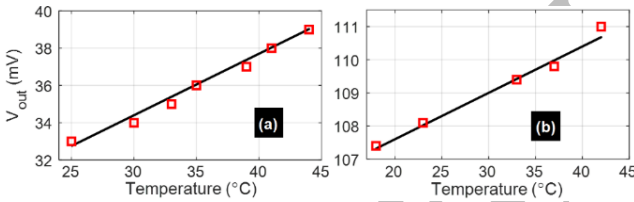


Fig. 8. Temperature influence on the WPG output voltage for a constant flow rate with (a) inner and (b) outer probe.

The fitted models of output voltages versus temperature are expressed by, respectively:

$$V_{out_inner}(T)=0.33T+24.5$$
 (mV) (3)

and:

$$V_{out_outer}(T)=0.14T+104.8$$
 (mV) (4)

with temperature T in $^{\circ}\text{C}$.

E. Conclusion on the WFT principle

As results of this section demonstration test, exterior probes are far more efficient to gather triboelectricity. Moreover, it is far easier to implement outer electrodes into a WPG, since it is not in contact with the water. Furthermore, such a device could be added more easily to an already existing installation such as irrigation pipes for example. Thus, we will only use outer probes from now on.

III. OPTIMIZATION OF WPG GENERATED VOLTAGE

The optimization approach of the WPG is elaborated in the present section by studying the impact of an additional probe and by two-pipe embedding.

A. Impact of additional probe

In order to improve the WPG performance, if the tank is at a given height, the best way to use the water potential energy is to let it flow in multiple short pipes in series as illustrated by Fig. 9(a). It is then natural to think that putting a series of probes separated by short distances on a single long pipe would work the same way. This is what was examined in this section: a third probe was added to the pipe, and slid to vary the distance between probes. The output voltage was measured with different distances and flow rates as represented by Fig. 9(b).

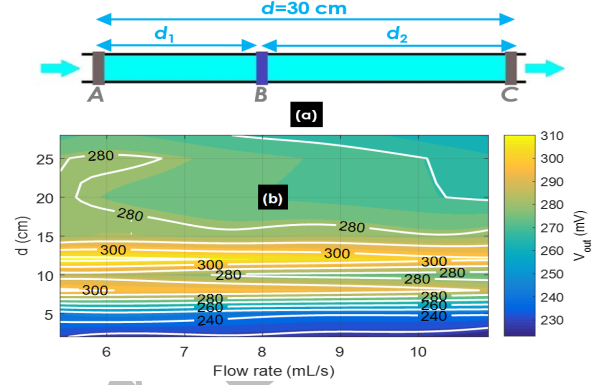


Fig. 9. (a) Illustrative diagram and (b) output voltage of inter-probe distance optimization.

Unlike it was expected, splitting the pipe in two pairs of electrodes is not like using two pipes equivalent lengths. Even more surprisingly, splitting the pipe $d=30$ cm in d_1 and d_2 is not equivalent to splitting it in d_2 and d_1 . The flow rate still has the same influence with any placing of the probes. Thus, this dissymmetry can be explained by an interior flow of charges influencing the potential difference between probes since changing the direction of the flow puts the maximum on the other side of the pipe. For the non-additivity, the reason could be a set maximum of charges that can accumulate on the pipe. Then, the first portion of the pipe (where is noticed a higher potential difference) would not suffer this limitation as much as the following ones. So, the solution would be to use separate short segments of pipes, which will be done later.

B. Performance of two-pipe embedding

Since triboelectricity is caused by friction between two bodies, it naturally comes to mind that increasing the friction surface between those will enhance triboelectricity generation. To maximize the surface between water and pipe, first came the idea to make the water flow around the pipe and not inside it. This water could then also be used to flow inside a second pipe. For this purpose, we embedded two pipes, one pipe of 4 mm diameter inside the second of 10 mm diameter, both are 0.7 mm thick. And, we made water flow between the two. Another advantage provided by this setup, is that there are three ways to get a potential difference putting electrodes: (i) on both ends of the outside pipe, (ii) on both ends of the inside pipe and (iii) between the inside and outside pipe.

Fig. 10(a) shows the experimental setup and the obtained measured output voltages are plotted by Fig. 10(b). The really low voltage for the inside electrodes and the inside-outside ones might be explained by an experimental difficulty: it was unmanageable to keep two pipes embedded without any contact between the two, so there might be points in the setup where the charge gets balanced between the two pipes, thus it cannot reach high values.

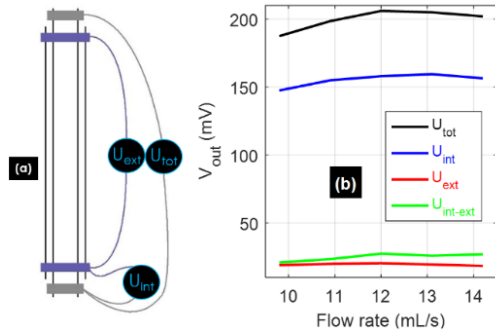


Fig. 10. Double pipe (a) setup illustration diagram and (b) measured harvested voltage.

A low flow rate is more efficient if the amount of water used to power the WPG is the limiting factor. In this sense, the two embedded pipes cause a real efficiency issue because higher flow rates at least 10 mL/s against 2 mL/s for the single pipe are needed to make the water flow around the whole inside surface and not only in small portions.

C. Conclusion on the WPG optimization

The efficiency of the different ways to implement the WPG is compared. It has to be acknowledged that the limiting factor in this study is the amount of water available, so the graph will include iso-efficiency curves under the form of different slopes linear curves. Efficiency represents a constant ratio of V_{out} under the invested water. Fig. 11(a) and Fig. 11(b) depict the abacus of different efficiencies for the case of inner (index “1”), exterior (index “2”), inner-exterior (index “3”) and total (index “4”) voltages from the simple and double pipe WPG, respectively.

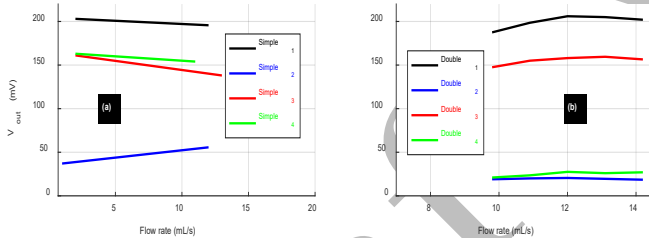


Fig. 11. Measured output voltage of (a) simple and (b) double pipe WPG with different inner and outer connections.

To design a WPG, a compromise between efficiency and feasibility must be chosen, thus, the adding of interior electrodes does not seem necessary, and the simple pipe with exterior electrodes seems to be the best choice. Moreover, it would be better to use several short pipes, than a long one with multiple electrodes.

IV. DESIGN OF THE FINAL LOW-TECH WPG

A low-tech WPG with recycling material was created with height single plastic pipes and two exterior electrodes as photographed in Fig. 12(a). The goal here was to combine the power of each generator to be able to power a low-consuming dipole like a LED. The length of each piece of pipe is $d_0=12$ cm. The pipe height was welded to a water bottle that has the role of a water tank. As presented in Fig. 12(b) and in Fig. 12(c), we tried to plug the WFT in serial or parallel to combine and optimize the output power, respectively. With these parallel WFTs, we can considerably increase the power of our device. The output voltage was around 90 mV for these characteristics on a simple pipe plugged to a 10 M Ω resistor.

The voltage gradually increases as we plug other pipes to reach 390 mV for 6 pipes, and 570 mV for 8 pipes.

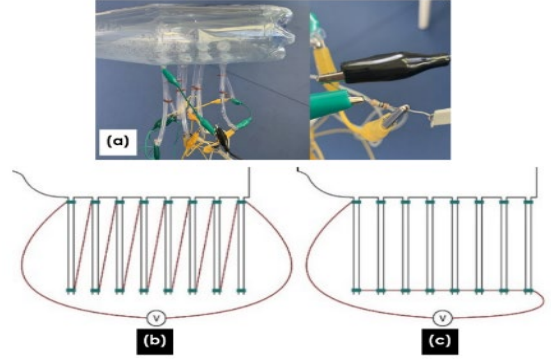


Fig. 12. The proposed pipes connection modes: (a) photo, (b) series and (c) parallel diagram.

The small variation of the potential, 390 mV against 540 mV expected, can be explained by the fact that the flow rate varies with height in the bottle as shown in Figs. 12. The left setup produces as much as a single pipe since each one of them discharges into the next one. Then, we tried the right setup that actually works like a parallel plugging. Without a charge resistor there is no voltage variation. But with a resistor the voltage increases every time a new pipe is plugged like previously. The cost of rain-TEG is extremely low due to a strategy of recycling certain elements such as: plastic bottle, plastic pipe, and twisted pair cable (copper from Ethernet cables).

V. CONCLUSION AND FUTURE WORK

Different ways of making triboelectricity thanks to rainwater were reviewed. In this study, we managed to get a first glance at the innovative possibilities to design and to build an affordable triboelectric generator (WFT) with recycling material. The main objective is to produce renewable energy with optimal technique approximately 200 mJ per liter of water. Different experimentations enable us to point out the effectiveness of the WFT technique generator that can deliver 100mV to 600mV. Such energy is planned to power enough low-consuming devices such as sensors or LEDs. Although the supply voltage is 1.5 V for an LED, it would be possible to use a charge pump. However, this generator will not have energy-storage issues because the main source is constituted by water. Although the energy and voltage level is low, it is not sufficient to autonomously power small IOT devices. We can still imagine many improvements for this generator, such as a flow rate controller that would optimize water consumption, or different materials to build the pipes.

Furthermore, this work proposes a technological breakthrough by not using materials doped with rare and expensive minerals, to increase energy recovery for nanogenerators in WFT technology. Our work respects the environment and offers new research directions and perspectives by using recycled materials to manufacture nanogenerators and recover energy cleanly from renewable sources as rainwater. Many of these devices can be stacked to gather more energy. The WFT is more common and easily installable in our project of rainwater harvesting and its flow along vertical pipe stuck to the building. After showing the efficiency of WFT, we explained how and with what we made the low-cost WPG with recycled materials.

These improvements would then make bigger generators able to power much more consuming devices. Thus, this affordable and recycling manner of producing electricity could be a great way to start giving autonomy to developing tropical areas. The proposed rain-powered energy harvester presents potential benefits on design accessibility, less fabrication cost, and high energy efficiency susceptible to replace the battery in low-power electronic devices.

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