International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 14, Number 12 (2021), pp. 1235-1243

Proposal for an Energy Harvesting System from Human Walking

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Abstract

Electric power has become an asset of great value worldwide, on which the development of an economy and the well-being of its inhabitants depend. Even so, there are regions in various parts of the world, particularly in poor economies, in which the inhabitants do not have this asset, in many cases vital for health and life. In Colombia, there are regions called Non-Interconnected Zones (ZNI), which are made up of small populations that due to their size and distance from urban centers do not have electric power distribution networks, because the costs exceed the income from energy sales. As a result, these areas remain without access to electricity, and their economic and social development is severely impaired. In recent years, countless studies have been carried out to provide energy to these areas from available energy resources under the microgrid model, however, there are still places where such solutions are unfeasible. An important characteristic of these places is the human presence, so it is proposed as a possible solution to the harvesting of electric energy from human activity in the areas. This research proposes the development of a low-cost piezoelectric system for use in small urban centres as a complement to other energy solutions in ZNI. The prototype platform is evaluated in the laboratory, demonstrating its feasibility and low cost.

I. INTRODUCTION

Currently, according to the Institute for Planning and Promotion of Energy Solutions for the ZNI (IPSE) [1], Colombia has a deficit in the provision of electric energy services, since only 48% of the national territory is in the national interconnected system (SIN), and 52% of the national territory that is in the ZNI, correspond to 78 municipalities, 18 special biodiverse and border territories, 1913 localities, 28 municipal capitals, and 5 departmental capitals. These areas are very dispersed and sparsely populated, the resources of the people residing in these areas are limited and their energy consumption is exceptionally low [2]. However, having abundant natural resources in the territory, such as solar and wind energy, there is a need to use these resources as a solution to the problems of these communities in the generation of electricity through non-conventional technologies [3].

There are multiple alternatives in the modern world to provide solutions to energy problems, such as solar, wind, biomass, and geothermal energy [4, 5, 6]. Nowadays, the concept of smart cities can be considered as territories that demand a much higher energy consumption than a conventional city, therefore they must be self-sustainable [7]. The energy demand required by these cities is exceedingly high, so it is necessary to design energy generation strategies in a clean and non-conventional way. A solution to this challenge is the generation of electrical energy using piezoelectric materials. A remarkably interesting alternative solution that contemplates the sophistication of the infrastructure in places where there is high vehicular and pedestrian traffic, to obtain energy and take advantage of these places without the generation of clean energy involves new spaces of the territory, using piezoelectric modules strategically located to take advantage of the kinetic energy generated by the traffic of a vehicle or a person when circulating through it [8, 9, 10]. By applying this type of energy solution in a city, transcendental changes can be achieved in terms of environmental benefits, since the pollution produced by traditional electric power generation is reduced. The social and economic impact is significant since with the generation of energy in areas of high vehicular or pedestrian flow, new ways of technifying cities can be proposed, some applications could be in external street lighting, signalling, and controlling pedestrian and vehicular flow [11, 12].

The concept of energy harvesting, which applies to the generation of electrical energy and is easily associated with piezoelectric generators, refers to the systems responsible for the recovery, reuse, and exploitation of diverse types of energy found in the environment and which are usually wasted. A study of harvesting using the method of topological optimization to maximize the generation of electrical energy produced by human beings performing daily activities, among some applications cited is the use of electrical energy through vibrations of the suspension of a bicycle [13, 14]. In the field of medicine, some researchers have been involved in producing electrical energy for certain implants that need it for their operation, thanks to technological advances and their tiny size they have been introduced into the human body and a clear example is the pacemaker attached to an artery that converts blood pressure into electrical power through pulses [15]. Within the daily activities, the greatest amount of energy that can be recovered is found in footsteps between 5 and 8.3 W of the 67 W consumed. Therefore, it is estimated that by harnessing energy in this way, the storage and supply of some important applications for the current study are guaranteed [16].

In Colombia, there are also some pioneering works. An interesting case is a study carried out in Soacha where a piezoelectric tile prototype was designed by A. Jaramillo, which has 15 35 mm PZT ceramic sensors inside, diode systems to rectify the output voltage signal, a capacitor to store the energy, generating a power of 6 mW per step, the structure of the tile has three layers: the first one for the protection of the tile, a second one for the protection of the sensors and base, this tile is designed to be used in the Transmilenio station of San Mateo due to its high flow of users that the station has, that of the total users of the municipality of Soacha, this station registers 54% of the total number of people who take the service [17].

In the city of Cali, the study consisted of estimating the feasibility of implementing Energy Harvesting systems in three scenarios that are three roads in the city, with names wide step, Simon Bolivar Avenue and Highway, having lengths of 1.35 km, 5.15 km and 1.22 km respectively [18]. With the statistical study was obtained that the vehicle flow for each of the roads is 1092 vehicles/h for wide step, 530 for AV. Simón Bolívar and 2554 on the highway, the model implemented in the proposal is the patented one because it consists of three collecting units each one with three piezoelectric batteries with capacity to generate 85 mW under a force of 1360 N and a frequency of 6Hz, for an average speed of 100 km/h each unit can generate 1 W, the patented module is composed of three generating units, for the design of the project it was proposed for each of the roads 2560 modules for wide passage, 3333 for AV. Simón Bolívar and 3300 for the highway, which will be installed in the speed reducers using a module containing a piezoelectric generator, with which 5.07 MWh, 23.254 MWh, and 18.794 MWh are generated respectively, being the energy generated of greater value that of the Avenida Simón Bolívar since for the solution approach it is the longest road, regarding the rate of return of the investment it is also the road with the highest IRR having a value of 16% [19].

The piezoelectric tile prototype built will allow estimating the amount of energy generated to evaluate some applications within the technological faculty, basing the results on a study of pedestrian flow at the entrance or exit of one of the entrances of the University. Thus, obtaining two applications that can be implemented by having a 1 m² platform composed of several tiles with the same characteristics of the prototype.

II. PROBLEM FORMULATION

The purpose is to propose and evaluate the design of a low-cost and high-performance piezoelectric tile for its use in the public areas of the Technological Faculty of the Universidad Distrital Francisco José de Caldas (Bogotá, Colombia). This faculty is characterized by a high population density with young people from the lowest economic strata of the city, but with high energy need given their technological training. The objective is that this prototype be installed by the university in places identified as high pedestrian flow, through an investment with the lowest cost and highest performance. The prototype will be evaluated from a technical and economic point of view, considering elements such as nominal energy generation capacity, estimated performance at the final point of operation, and economic evaluations of its implementation.

III. METHODOLOGY

PZT (Lead Titanate with Zinconate) is the most widely used piezoelectric in the industry. It is designed from synthetic materials that form a structure called Perovskite. The principle of operation is given by its central atom (titanium or zirconium) which moves when deformed creating a molecular polarization. It is the most widely used of the piezoelectric materials due to its low cost and its good physical and piezoelectric properties. For the prototype, we selected a piezoelectric module with a maximum generation voltage of 15 V and a maximum current of 8 mA.

For the characterization of the piezoelectric, a series of tests were developed to determine the best material according to its physical and mechanical properties, considering the section that will be in contact with the piezoelectric ceramic. For this purpose, distinct types of materials are chosen to see the deformation behavior of the piezoelectric. Intentionally several types of materials widely available locally with low cost, with low hardness, are chosen to reduce the wear of the piezoelectric. Six materials are taken for this purpose:

- Rubber
- Wood: Balsa
- Bakelite
- PLA (Polylactic Acid)
- Coil leather (grain side)
- Coil leather (flesh side)

To describe the mechanical properties of the materials, it is considered factors that directly affect the deformation behavior of the piezoelectric through the action of continuous or discontinuous, static, or dynamic external forces exerted on them. Therefore, the study of the mechanical properties of the materials is especially important when choosing the material to build the piezoelectric tile design (Tables 1 and 2).

- Rubber: The raw materials used to manufacture tires are rubber, carbon black, metal, textile, chemical additives, however, the component that is found in greater proportion is a mixture of synthetic rubber.

- Balsa: Balsa wood is a tropical wood with optimal characteristics for its easy workability. It has the lightest weight among all tropical woods. The main property of Balsa wood is the relationship between its extremely lightweight and its high resistance and stability, being this its most outstanding quality.
- Bakelite: It is a polymeric resin of phenol and formaheid. It is characterized by its high mechanical strength and good dielectric properties, as well as its resistance to corrosion.
- PLA (Polylactic Acid): A compostable thermoplastic polyester of natural origin, it has good mechanical properties compared to those of standard thermoplastic materials. PLA hardness, rigidity, impact resistance, and elasticity are like PET.
- Leather: It is one of the most versatile materials known. This is due to the unique arrangement of the complex natural fibres that occur in diverse types of hides and skins. Chemical and physical processes are tailored to allow for specific properties and performance as they are converted into leather.

Table 1. Test materials properties (similar materials)

Properties	Bakelite	Balsa	PLA
Tensile strength	High	Medium	High
Bending strength	High	Low	Very high
Impact resistance	Low	Low	Very low
Compressive strength	Very high	Medium	High

Table 2. Test materials properties (comparable materials)

Properties	Rubber	Leather
Durability	High	Very high
Breaking strength	Medium	High
Abrasive resistance	Medium	High
Compressive strength	High	Very high
Tensile strength	High	high

To perform the mechanical tests, the structure shown in Fig. 3 was implemented. It consists essentially of two metal plates, one upper and one lower, which will serve as protection for the piezoelectric. It also has four springs and four screws for the adjustment and return of the displacement of the upper plate. In the upper sheet will be adhered the different materials with which the piezoelectric will interact, the tests to characterize the behavior of the piezoelectric consists of pressing the upper sheet with the force of a footprint of an adult person, a man with 70 kg of weight, register the tension value and the tension waveform that generates according to the type of material that is in contact with the piezoelectric, the form that is given to the different types of materials is rectangular covering the entire ceramic surface of the piezoelectric, i.e. a piece of material of 5 cm by 3 cm, and a thickness 0.4 cm.

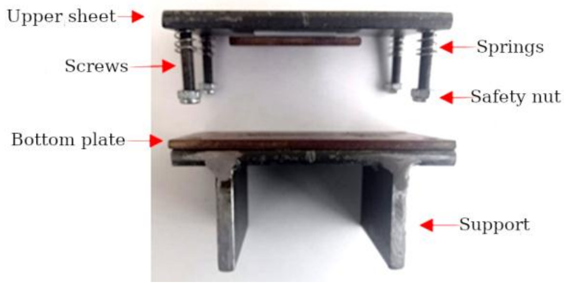

Fig. 1. Mechanical device for testing the coupling material

The RIGOL DS1102E oscilloscope was used for test data acquisition. Multiple tests were performed with each of the materials. Figs. 2 to 7 show some of the resulting curves.

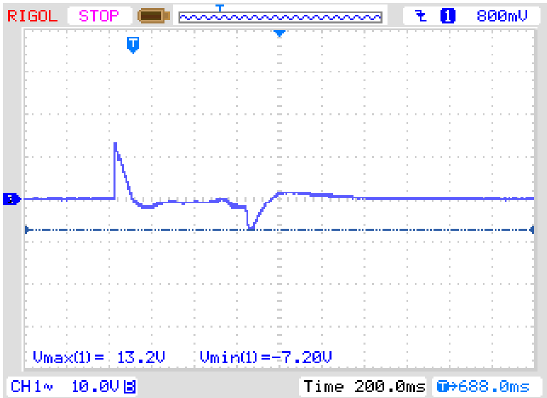

Fig. 2. One-step transducer electrical response using rubber

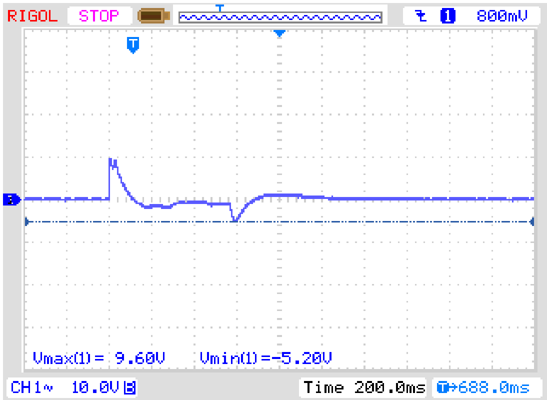

Fig. 3. One-step transducer electrical response using balsa wood

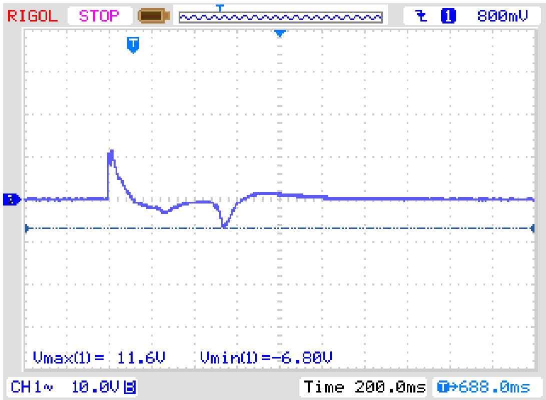

Fig. 4. One-step transducer electrical response using PLA

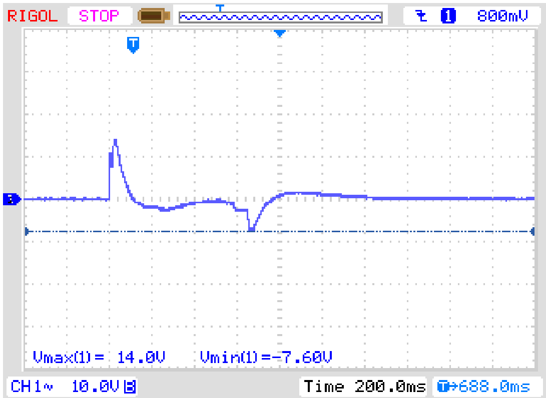

Fig. 5. One-step transducer electrical response using bakelite

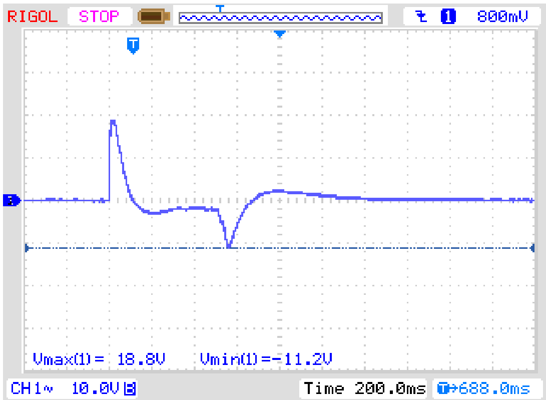

Fig. 6. One-step transducer electrical response using leather grain side

According to the results of the piezoelectric performance tests, the material with the best interaction is leather on the flesh side, this is due to the mechanical characteristics of leather, its elasticity when in contact with the piezoelectric makes it adapt and occupy more area in the ceramic section, achieving a greater deformation in the piezoelectric. This material reached a higher average and peak voltage value than the other materials. Electrical performance tests were performed for various loading conditions to characterize the prototype, the results are shown in Fig. 8. The operating range of each part was established between 10 and 15 V.

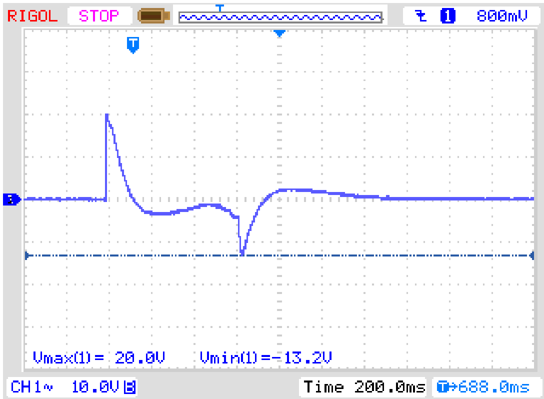

Fig. 7. One-step transducer electrical response using leather flesh side

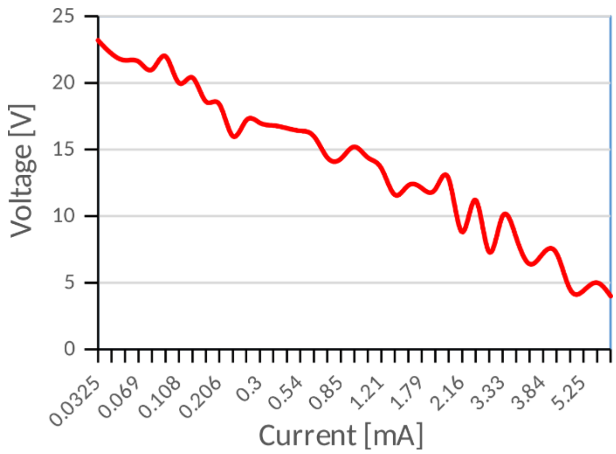

Fig. 8. Electrical performance of the piezoelectric with the selected material

Based on the results obtained from the piezoelectric behavior, the piezoelectric tile is designed to scale with a total of 14 piezoelectrics distributed uniformly over an area of 900 cm². The quantity and distribution of the piezoelectrics are defined according to the size of the tile and seek to take advantage of the greatest possible amount of energy. The piezoelectric dimensions are taken into account so that the piezoelectric is very close to the total area of the tile (Eq. 1).

$$\text{Piezoelectric area} = 8\text{ cm} * 3.3\text{ cm} = 26.4\text{ cm}^2 \quad (1)$$

To determine the number of piezoelectrics covering the entire tile, a tile utilization factor of 45% is used, omitting the spaces between the piezoelectrics and other spaces to integrate some mechanical systems. This gives an effective area of 405 cm^2. According to the piezoelectric area of Eq. 1, a total of 15 piezoelectrics are defined for each tile. However, due to physical constraints, 14 were installed in the construction process to perform all voltage, current, and power generated tests.
To verify the behavior of the piezoelectric tile, individuals with an average weight of 70 kg are taken into account according to the age range of students, professors, and staff entering the Universidad Distrital, Technological Campus. It is determined that the highest percentage is found in students who leave school directly to the university and are in the range of 18 and 25 years of age. Thus, the general strength to perform the tests was calculated according to Eq. 2.

$$F = m\,a = 70 \text{ kg} * 9.8 \text{ m/s2} = 686.47 \text{ N} \qquad (2)$$

According to the studies developed in the generation of energy using piezoelectric generators, the mechanical system is an essential part of the development and capacity of energy generation. That is why some characteristics such as geometric shape, ease, and reliability were taken into account to generate energy in the most optimal way. According to the study, the best tile geometry-shape to generate the most energy is square. According to the displacement analysis of the deformation point, this is taken as a reference point for the development of the tile. Similarly, a standard footprint area covering all areas of the foot in any direction is taken.

The mechanical system implemented is shown in Fig. 9. The materials used for the final construction are as follows:

- 2 steel sheets of 900 cm^2.
- 1 bakelite sheet of 900 cm^2.
- 4 springs of 10 mm in diameter by 6 cm in length
- 4 screws 6 mm in diameter by 8 cm in length
- 14 leather sheets of 3 cm by 5 cm
- 4 safety nuts of 6 mm
- 1.3 cm angle

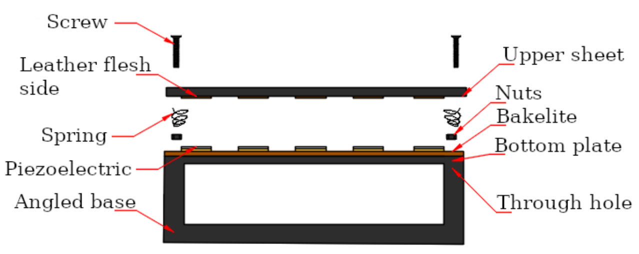

Fig. 9. Mechanical tile system

A robust mechanical system was proposed that would be able to withstand large amounts of pedestrian traffic without deteriorating the materials. In addition, we sought to ensure that the steel plates would distribute the force of the footfall over the entire surface of the bottom plate, and activate as many piezoelectrics as possible, and in turn generate more energy. A bakelite sheet was installed on the bottom sheet to avoid energy losses in the piezoelectrics, i.e., each piezoelectric has an independent connection, and could facilitate the different electrical connections during the tests.

The spring force is greater than the weight of the sheet to have a separation of approximately 5 mm between the sheets and to have greater kinetic energy applied to the piezoelectrics when the step force is generated. Fig. 10 shows the distribution of the 14 piezoelectrics in the bottom sheet supported on the Bakelite. In addition, four holes were drilled in the corners for the screws to pass through, which are the guides for the activation of the piezoelectrics. The springs chosen to the measure to overcome the force of the upper plate and to have a separation of approximately 5 mm are assembled through the lower and upper plate.

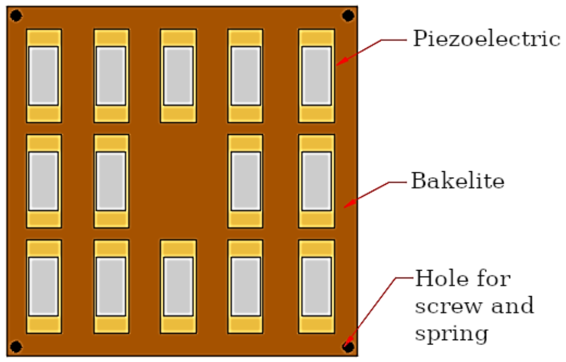

Fig. 10. Bottom plate of the mechanical system

Once a force is applied to the upper sheet, the weight will be greater than the force exerted by the springs and the upper sheet will lower so that the leather strips can make contact with the piezoelectric, and can deform the material to generate a tension in each of the piezoelectric terminals.

IV. RESULTS AND DISCUSSION

With the development of the mechanical parts of the tile, we proceed to perform the tests with the piezoelectrics distributed as shown in Fig. 11. For the tests three types of connection are chosen, all piezoelectrics in parallel, with all piezoelectrics in series and a third mixed configuration which through tests was obtained that the best combination is to have two sets of five piezoelectrics in parallel, and one set of four piezoelectrics in parallel, and these sets in series. The following shows the final results of connection, for these tests are made with the footprint of a person of average weight in Colombia of 70 kilograms, connecting to the output different load values in a range of 680 Ω to 1 MΩ.

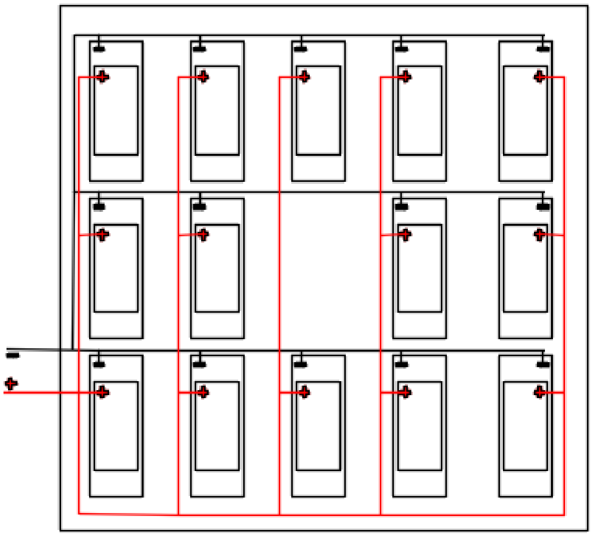

Fig. 11. Scheme of mixed connection used in the tile

The connection is composed of three series arrays, two of which are made up of five piezoelectrics in series, and one of four piezoelectrics in series with this configuration. It was evidenced in the tests that it had a better performance in voltage and current concerning the parallel and series connections. The values recorded in the measurement equipment can be seen in Tables 3 and 4.

Table 3. Voltage at terminals for different loads in mixed connection

Resistance [kΩ]	Test 1 [V]	Test 2 [V]	Test 3 [V]	Voltage [V]
0.68	4.65	5.71	4.40	4.92
1.0	4.65	6.88	6.33	5.95
2.2	9.05	8.99	8.12	8.72
5.1	11.22	10.29	11.72	11.08
10	16.56	15.75	16.12	16.14
22	18.97	15.25	19.22	17.81
51	22.01	21.58	22.14	21.91
100	19.41	23.19	24.56	22.39
220	24.93	24.43	26.6	25.32
560	25.61	29.39	27.22	27.41
680	29.39	26.91	26.54	27.61
1000	28.9	30.32	34.17	31.13

Table 4. Current for different loads in mixed connection

Resistance [kΩ]	Test 1 [mA]	Test 2 [mA]	Test 3 [mA]	Current [mA]
0.68	7.55	7.85	9.24	8.21
1.0	6.7	8.7	6.52	7.31
2.2	7.13	7.91	6.91	7.32
5.1	4.65	4.89	4.05	4.53
10	3.26	2.84	3.26	3.12
22	1.15	1.21	1.15	1.17
51	1.20	1.09	0.91	1.07
100	0.31	0.37	0.43	0.37
220	0.24	0.20	0.16	0.20
560	0.082	0.093	0.092	0.09
680	0.067	0.054	0.063	0.06
1000	0.035	0.043	0.044	0.04

Fig. 12 shows the behavior of the connection, the current values in this test did not vary greatly concerning the parallel connection, but the voltage values did increase compared to the other two types of connection, having a maximum voltage value of 31.13 V.

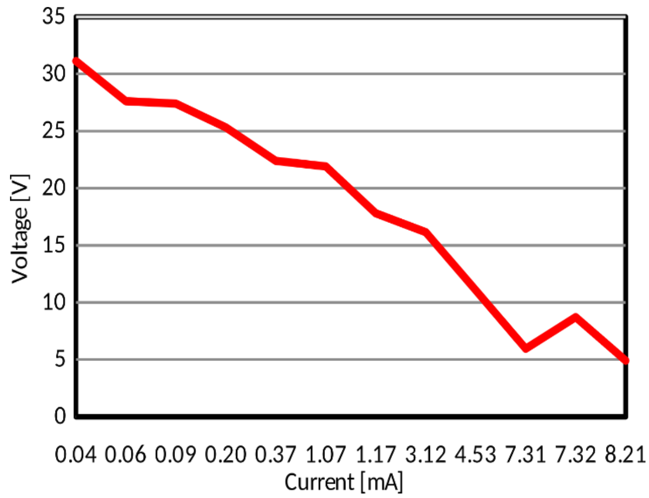

Fig. 12. Voltage vs. current graph in mixed connection

According to the chosen operating range of the tile, for applicability and efficiency, the mixed configuration has the highest generated power value per step with a value of 50.37 mW at a voltage of approximately 16.14 V (Fig. 13). This is the type of connection that will be used to calculate the electrical

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 14, Number 12 (2021), pp. 1235-1243

power generation of the piezoelectric system. In the same way that the piezoelectric generator was characterized, a minimum value of energy is guaranteed when the foot is not completely pressing the tile but in 25% and 50% obtaining for this case the values of Table 5.

Fig. 13. Complete footprint on piezoelectric tile

Table 5. Estimation of power generated per tile according to the effectiveness of the footprint

Area [%]	Resistance [kΩ]	Voltage [V]	Current [mA]	Power [mW]
100%	10	16.14	3.12	50.37
50%	10	14.49	2.10	30.38
25%	10	11.25	1.33	14.95

Taking into account the statistical study of pedestrian flow through the main entrance of the technological campus, as the average hourly pedestrian flow obtained, and with a projection of pedestrian flow through one of the faculty's entrances per day, month and year, considering 16 hours of classes per day, 20 days of classes per month and 10 months of classes per year, the utility data shown in Table 6 can be projected.

Table 6. Estimated performance of the tile according to pedestrian flow

Hourly work fraction	Pedestrian outings per week	Average pedestrian flow per hour	Pedestrian flow	
			Month	Year
Antes de 6:00 a.m.	145	29	580	5,800
6:00 am - 7:00 am	334	67	1,336	13,360
7:00 am - 8:00 am	1,847	369	7,388	73,880
8:00 am - 9:00 am	1,537	307	6,148	61,480
9:00 am - 10:00 am	3,870	774	15,480	154,800
10:00 am - 11:00 am	2,066	413	8,264	82,640
11:00 am - 12:00 m	4,443	889	17,772	177,720
12:00 m - 1:00 pm	3,445	689	13,780	137,800
1:00 pm -2:00 pm	4,121	824	16,484	164,840
2:00 pm -3:00 pm	2,175	435	8,700	87,000
3:00 pm -4:00 pm	4,066	813	16,264	162,640
4:00 pm -5:00 pm	2,351	470	9,404	94,040
5:00 pm -6:00 pm	4,669	934	18,676	186,760
6:00 pm -7:00 pm	2,174	435	8,696	86,960
7:00 pm -8:00 pm	4,302	860	17,208	172,080
8:00 pm -9:00 pm	1,315	263	5,260	52,600
9:00 pm - 10:00 pm	1,967	393	7,868	78,680
After 10:00 pm	19	4	76	760
Total: Pedestrian outings per week	44,846			
Total: Pedestrian flow per day		8,969.2		
Total: Pedestrian flow per month			179,384	
Total: Pedestrian flow per year				1,793,840

V. CONCLUSION

With the development of this project, it was possible to analyze the behavior and quantify the amount of energy that can be obtained by making a piezoelectric tile and could see that in terms of the technical part if the applicability of this type of technology for power generation is viable, but economically there are better options since the piezoelectric materials are quite expensive, for example, a 400 W solar panel has a current market cost of approximately USD 172 and the tile of USD 171 and its generation is very short compared to the solar panel.

For the development of the characterization of the piezoelectric module we proceeded to manufacture a mechanical device that would allow pressing the module in its entirety without damaging it, so we devised a way to protect the ceramic material of the module, so several materials were tested in contact with the surface and the one with the best test results was chosen, which consisted of stepping on the mechanical device designed for this purpose, with an average step of a person weighing 70 kilograms, and with the data and waveforms of the voltage signal, we proceeded to design the tile and the electrical circuit, and with the electrical circuit and tile built, some tests similar to the characterization of a single module are performed, and a variable load is connected to analyze the behavior of the tile under load and to finish with the development, some possible applications are projected according to the results delivered in the tests.

When performing the tests the following results were obtained, the best material for ceramic protection and in contact with it is leather, it was the test that best voltage values recorded in the measurement equipment, another important test that was executed is the type of connection between the piezoelectric modules and it was found that the most favorable connection for the generation of electrical energy of the tile is the mixed connection because in terms of current is similar to the parallel connection, but in voltage, it behaves much better having maximum values of more than 30 V.

When finding a suitable capacitor for the signal rectification circuit, it was found that the commercially required value is not available in the market because it was necessary to recalculate the signal ripple value, which went from 10% to 14%. 5% for the proposed applications is not a determining value since most electrical appliances have an integrated rectification circuit, the test that is convenient to perform is to section the tile area in 100%, 50%, and 25% which was done to ensure a minimum power generated which would correspond to the part of the foot as mentioned above, the energy generated by the piezoelectric platform depends mainly on the number of people passing through it, in the case that the platform is 1 m², a person could step on the platform 1.69 steps thus generating power of 0.76 W.

This type of technology can be implemented in other strategic places of the University due to the continuous increase of students that enter annually, the behavior of the energy generation is proportional to the number of students that surround the areas of the faculty, for example, in the parking lot, cafeteria and areas where students frequent the most. In addition, some applications can be implemented to feed low power loads in DC and thus increase the efficiency of the tile by 10%.

ACKNOWLEDGMENTS

This work was supported by the Universidad Distrital Francisco José de Caldas, specifically by the Technological Faculty. The views expressed in this paper are not necessarily endorsed by Universidad Distrital. The authors thank all the students and researchers of the research group ARMOS for their support in the development of this work.

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