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Abstract—The new generation of artificial muscles for the movement of electromechanical systems is based on ionic electro-active materials that can extend and contract depending on the applied electric voltage or current, acting as a natural muscle. These materials may also operate in generator mode, where mechanical energy is converted into an electrical signal - this is the subject of this study. Based on previous works a theoretical electromechanical model of the IPMC (Ionic Polymer Metal Composites) material was deduced. A electromechanical twist device which converts mechanical energy into electricity was built, modeling the oscillating motions around a joint, emulating the motion of the human elbow. This electromechanical system uses a single piece of composite material, which when subjected to certain mechanical stresses gives rise to an internal ionic current responsible for electric loading the capacitive part of IPMC material, a concept also known as energy harvesting. Experiments were conducted with several IPMC material strips of different thicknesses, subjected to mechanical stresses of different intensities, both axial and transverse, and using different concentrations of solute in the electrolyte. The results show a gradual increase of power density observed when is increased the value of several variables, i.e., the value of the electrolyte concentration, the angle that the IPMC strip is subjected and the intensity of the force applied, but this is only valid within a certain limit.

Index Terms— Electromechanical converter; Energy Harvesting; Artificial Muscles; Ionic Polymer-Metal Composite; IPMC; Intelligent Materials; Electroactive Materials.

I. INTRODUCTION

The technological developments are increasingly tending to miniaturization and portability. At present we are completely dependent on many devices of this type, such as mobile phones, mp3 players, ipads, and much more. There is still a big leap to make in the evolution of these devices, which is its storage form, or to generate energy for them work. Imagine, for example using the energy of the huge movements or vibrations from the human body, which is an energy from renewable sources, and that is an extra reason to further promote its development.

Therefore it is important to study new forms of energy generation usable on a limited scale. This is where the material which is based the study of this thesis comes from, the IPMC (Ionic Polymer Metal Composite).

Such materials are relatively new and still have a small range of studies, but are often named as artificial muscles, since they have mainly been reported as actuators [1-5], in this type of operation is found that with a small current they have movements of large amplitude [3].

They can be compared to other materials with characteristics very similar to IPMC, known as piezoelectric material [6, 7, 22-27], these ones exhibit some differences, since they have a high mechanical stiffness so they don't have flexibility, and to generate electrical power they need very high mechanical stress [7]. IPMC material presents a major advantage over these, because it does not require high values of stress, it is extremely flexible and can therefore be applied to a variety of systems much greater than the piezoelectric materials.

The experimental mechanism used in most traditional systems [2,6,7,8,9,11], consists in applying a deformation on a restricted area on the IPMC pieces. For these, they are fixed at one end and the other is applied forces that cause the deformation. Thus, most of the IPMC area is unused because there are not significant internal mechanical stresses. There is also another reference in the literature [16], which uses a different approach, where their conversion mechanism is intended to apply stress to the entire surface of the IPMC film, compressing it uniformly affecting the entire piece.

Thus, most of the IPMC area is unused because there are not significant internal mechanical stresses. There is also another reference in the literature [16], which uses a different approach, where their conversion mechanism is intended to apply stress to the entire surface of the IPMC film, compressing it uniformly affecting the entire piece.

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This work came in continuation of [16] and it is intended to characterize the operation of IPMC material as an energy harvesting device, based on its total surface use, particularly when subjected to "pulse" periodic axial and transverse stress, based on the movement of human elbow, converting this mechanical energy into electrical energy, as seen in Fig. 1.

An exhaustive experimental analysis has been done to develop electromechanical models, which are compared to theoretical models that were developed in order to predict the dynamic and electrical behavior of the IPMC transducers in generator mode.

II. IPMC ELECTROMECHANICAL MODEL

Whereas that IPMC material acts as an energy harvesting system, his theoretical model can be divided into two parts, the mechanical and the electric one. The first part is about the internal mechanical stresses due to internal stresses when applied external stress, and the second part discusses the positive ion electric current, the induced charge in the electrons and the resultant electric field distributions inside the IPMC.

A. Mechanical Model

To study the mechanical model is considered the inferences made in [12] which is discussed a general scope of this subject, and then a more specific model was developed and adapted to the mechanism used in this experimental tests.

In this case IPMC is subjected to axial stresses and also transverse stresses. The displacement of the ionic charges caused by internal mechanical stress and consequently the current and power densities generated is maximized.

This approach is based on a uniform distribution of strain in the entire volume of material IPMC. Which is achieved in a first experimental step, by applying a uniform axial stress, which will affect the entire volume of the IPMC sheet. This stress was being made on $x_1$ direction, there was an extension, and this causes a displacement in the same direction, but for this study this displacement is irrelevant, it also led to a second displacement on $x_2$, which is the most relevant. In the second experimental step was carried out not only the axial stress from the previous step, but also introduced the angle factor, which will cause transverse stress, and in this case was a visible a increase in current density and power generated by IPMC, because the displacement in the direction $x_2$ was more evident.

Starting from the general mechanical model of IPMC, can be seen at Fig.2, and after doing the same considerations made at [12] and [16], we have the movement equations (1).

$$
\rho \frac{\partial^2 \delta_1}{\partial t^2} = \frac{\partial \tau_{11}^{\text{me}}}{\partial x_1} = \frac{\partial \tau_{12}^{\text{me}}}{\partial x_2} + \frac{\partial \tau_{22}^{\text{me}}}{\partial x_2}
$$

From (1) its seen that there are no components under $x_3$ direction, that is because it was assumed that there are no significant forces in that direction. Based on that we can reach the relations between the material deformation $e_{ij}$ and displacement $\delta_i$ that are given by (2).

$$
e_{11} = \frac{\partial \delta_1}{\partial x_1} = \frac{1}{\rho} \left[ \tau_{11}^{\text{me}} \right]; \quad e_{22} = \frac{\partial \delta_2}{\partial x_2} = \frac{1}{\rho} \left[ -v \tau_{11}^{\text{me}} \right] \quad (2)
$$

On the development of equations (1) to obtain the displacement equation on the $x_2$ and $x_1$ directions, it is seen that due to the thickness of the IPMC when compared to the other dimensions on Fig.2, its behavior can be approximated by a one-dimensional model, since the displacement in the direction $x_1$ is almost zero, then negligible, being $\delta_1 \approx 0$.

Taking into account all design and details described in [12], and all of the foregoing we obtain the final equation of motion (3).

$$
\rho \frac{\partial^2 \delta_2}{\partial t^2} = \frac{1}{2} \left( x_2^2 - \left( \frac{x_2}{2} \right)^2 \right) \frac{\partial \int \frac{\partial \delta_1}{\partial x_1} \left( 2G + \lambda \right) v - \lambda \frac{\partial \delta_1}{\partial x_1} + F_{e2} \right) \quad (3)
$$

Using the specific characteristics adopted to the form as will be conducting the experimental tests, it is possible to approximate the general mechanical model to a more specific one, adjusting the results for the specifications of this unique study.

![Fig.2 - Fixed IPMC sheet and axis.](image)

Deduced the mechanical internal stress will have only the component on $x_2$ direction, given by (4).

$$
T_{22}^{\text{me}} = (2G + \lambda) \frac{\partial \delta_2}{\partial x_2} + \lambda \frac{\partial \delta_1}{\partial x_1} \quad (4)
$$

In conclusion the mechanical model adapted to this particular case, has its movement components and subsequent generation of electrical energy dependent on the stress.
responsible for the movement imposed to IPMC on \( x_1 \) direction. But, as seen above, this is not the direction which is responsible for obtaining the motion energy, then the movement carried out in the direction \( x_2 \) is directly related to the stress on \( x_1 \) by the Poisson's ratio \( v \).

B. Electrical Model

As was made in the point A, the electrical model used the general form in [12], and then it was adapted for the specific electro-active IPMC generator when submitted to axial stress tests.

It is assumed that the IPMC material is made of three species: mobile ions, fixed negative ions, and \( \text{H}_2\text{O} \) molecules. But the negative ions are chemically fixed to the Nafion structure, and the resultant force experienced by them is null, so only the positive ions and water molecules will be significant for the IPMC electrical model.

As water molecules have a higher mass density than the positive ions (\( \rho^h \gg \rho^+ \)) and since the positive ions speed is assumed to be greater than that of the water molecules (\( v^+ \gg v^h \)), momentum equations of ion and water are given by (5).

\[
\frac{d(\rho^+ v^+)}{dt} = F^+ = 0 \quad \frac{d(\rho^h v^h)}{dt} = F^h = 0
\]  

Neglecting the microscopic composition and giving an increased interest at macroscopic structure, since it's assumed a particular interest in studying the movement and power densities in IPMC samples, and whereas these phenomena rely almost exclusively on mobile ionic charges in detriment of water molecules, the analysis will be focused on the positive ionic charges and their power densities.

\[
F^+ = F^c_+ + F^d_+ + F^p_+ + F^n_+
\]  

In (6) is represented the total force density \( F^+ \) that depends on the electrostatic force density \( F^c_+ \), on the force density due to the diffusion process \( F^d_+ \), on the force density due to the space variation of mechanical stresses acting on positive ions \( F^p_+ \), and on the friction force density applied to positive ions by water molecules \( F^n_+ \). The development of all this parameters can be seen at [12], using that and knowing the total force density on the positive ions is assumed to be in equilibrium, because of the absence of significant effects of acceleration, it results in the positive ions density current \( J^+ \), that after developed is given by (7).

\[
J^+ \equiv -D_f \nabla \rho^c_+ - L_p \nabla \rho_{mec}
\]  

Where \( \nabla \rho_{mec} \) represents the stress gradient, \( L_p \) is related to the intensity of the force that IPMC is subjected, \( D_f \) is the diffusion coefficient, and is assumed that this parameter exists only before the experimental tests in the preparation settings, thus, the conditions of concentrations of positive ions inside the IPMC structure are kept during the tests. The diffusion coefficient can be neglected for further simplification of the expression for the positive ions density current at (8).

\[
J^+ \equiv -L_p \nabla \rho_{mec}
\]  

With this expression (8) the significant dependence of the ionic current \( J^+ \) is verified for the mechanical internal stress gradient \( \nabla \rho_{mec} \) resulting from external mechanical stress imposed on experimental tests. This parameter can be seen on Fig.3. Based on the above, comes that the ion current density is directly proportional to the gradient of mechanical force applied and the parameter \( L_p \), this is mostly conditioning, as seen in (9), by the friction constant \( K \), which decreases it, and for the density of positive charge \( q^+ \), which increases it.

\[
L_p = \frac{q^+}{K_p}
\]  

Fig.3- IPMC physical model configuration [12].

Thus, assuming IPMC is not in a saturation state, as the examples showed in Fig.4, where IPMC is saturated because of very high electrolyte concentration Fig.4(a), and because of very high force applied Fig.4(b), is safe to say, according to this theoretical model, the flow of ionic charges \( J^+ \) increases with increasing electrolyte concentration and also with increasing external stress applied. An example of this situation, when force is applied on the IPMC sheet without reaching the saturation point, can be seen at Fig.5.

Fig.4(a) - Saturated IPMC sheet: very high electrolyte concentration.
C. Equivalent Electrical Circuit

Here it will be made a representation of the lumped equivalent model of the IPMC generator as shown at Fig.6, to obtain the electrical characteristics of this system.

The basic configuration of the IPMC electro-active generator intended to be modeled is shown in Fig.3 and Fig.5. It consists of a small rectangular plate of IPMC material, through which a positive ion current density $J_+$ is flowing.

\[ i = \frac{24\varepsilon b l D_f}{5 \lambda} V - \frac{1}{\lambda} \int_0 \frac{d}{d} [\nabla p_{mec}] d x_1 d x_2 + \frac{3 s b l}{5 \lambda} \frac{d}{dt} (10) \]

In (10) is shown the relation between voltage and current, this one is the component $i$ at Fig.6. The other parameters on this figure can be taken from (10) too

\[ R_{dif} = \frac{5}{24 \varepsilon b l D_f} ; \quad (11) \]

\[ C_{eq} = \frac{3 s b l}{5 \lambda} i ; \quad (12) \]

\[ I_{mec} = -\frac{1}{\lambda} \int_0 \frac{d}{d} [\nabla p_{mec}] d x_1 d x_2 \quad (13) \]

In (11) is represented the internal resistance of the IPMC film, in (12) is the electric capacity, and last in (13) is shown the current due to mechanical stresses. From the electrical point of view the resulting set of internal mechanical stresses existing in the IPMC is directly related to the electrochemical interaction, with the current source $I_{mec}$ at his origins.

III. CHARACTERIZATION OF IPMC SHEETS AS HARVESTING SYSTEMS

Two experimental steps will be considered in order to have a greater rigor in the conclusions drawn from the experiences. In the first stage IPMC are subjected only to axial stresses, with an angle of $0^\circ$, i.e., forces are applied which cause a extension of several sheets, one at a time, with different thicknesses. The second step is similar to the first but in addition to the axial stresses, there are also applied transverse stresses while the experimental mechanism is inclined at
different angles of 0°, for a range of forces with more differentiated intensities, and for safety reasons only the sheet of smaller thickness is used, since in these cases the physical damage of sheets could be permanent, another reason is the good results observed to this sheet in the first experimental step. In both experimental tests are used different types of electrolyte concentrations.

A. Experimental Setup

The IPMC material used was purchased from Environmental Robots [15]. Furthermore, the different manufacturing process [8, 11, 13, 14] used in IPMC generators may show different physical characteristics due to the geometrical specifications required and the high variance of results inherent in the manufacturing process, these phenomena is evident in the used IPMC pieces as shown in Fig. 7, and their dimensions are shown at Table I.

<table>
<thead>
<tr>
<th>IPMC</th>
<th>Thickness (mm)</th>
<th>Width (cm)</th>
<th>Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0.2</td>
<td>1.20</td>
<td>4.40</td>
</tr>
<tr>
<td>(b)</td>
<td>1.2</td>
<td>1.15</td>
<td>4.30</td>
</tr>
<tr>
<td>(c)</td>
<td>3.0</td>
<td>1.10</td>
<td>5.35</td>
</tr>
<tr>
<td>(d)</td>
<td>4.0</td>
<td>1.20</td>
<td>8.50</td>
</tr>
</tbody>
</table>

An IPMC generator is made of composite material consisting of two distinct parts: a central layer made of electro-active polymer called Nafion-117 by DuPont and two platinum electrodes deposited on the top and below of each polymer surface. Nafion polymer is characterized as having fixed on its structure negative charges that provide selectivity to the polymer, making it only permeable to positive ions solutions. The manufacturing process of the electrodes consists on the deposition and crystallization of the metal on the surface of the polymer so that metal could form a porous cover, with crystal capillaries, called dendritic structures, which penetrate inside the polymer structure.

In Fig. 8 is shown the experimental mechanism used in this study. One of the nonuniformly charged IPMC generators is hydrated a couple of hours before the experimental tests, with a electrolyte composed by of salt and water. The electro-active IPMC generator is fixed between the upper arm the movable lower arm, as seen in Fig. 9.

A scale of weight is put inside the container to apply uniform force over the IPMC, as shown in Fig.8.

The outputs of this system are two electric terminals fixed to the platform where the oscilloscope measures the voltage response, having a resistive charge of 1MΩ put in parallel on this terminals. The oscilloscope is connected to the terminals of the electric wires that are connected to the electrodes, as can be seen on Fig.10.
B. First Experimental Step: Axial Stresses only

In this case all the stresses applied to IPMC are purely axial, and always having the same intensity, the inclination angle is only 0°. These conditions were used for the following concentrations of solute (NaCl - sodium chloride) per liter of solvent (H2O - Water): 5g/L, 10g/L and 20g/L. Here are used the four IPMC sheets shown in Fig.7, since the risk of permanent damage is minimal.

Knowing that the Young’s modulus for the weakest situation, i.e. for the 0.2mm of thickness sheet [18, 19] is \( E = 9.6 \text{ MPa} \), the maximum mass that can be put in the experimental mechanism is 2.33Kg, so the mass calculated to put in this experimental step is 1.132Kg, making a mass variation of 1Kg, to not having any risk of rupture of any sheet.

But the considerations that will be subsequently made are not related to weights but stresses, so based on the dimensions of the IPMC sheets and weight that will gone to be used on them, mechanical stresses are calculated, \( P_{\text{mec}} \), on each one of the sheets, as can be seen in Table II.

<table>
<thead>
<tr>
<th>Thickness [mm]</th>
<th>( P_{\text{mec}} ) [N/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>4.08x10^6</td>
</tr>
<tr>
<td>1.2</td>
<td>7.10x10^5</td>
</tr>
<tr>
<td>3.0</td>
<td>2.97x10^5</td>
</tr>
<tr>
<td>4.0</td>
<td>2.04x10^5</td>
</tr>
</tbody>
</table>

The best way to characterize the ability of generating from IPMC is proven through the power densities, i.e. these being defined as being power per unit volume.

This choice is due to two main reasons: the first is the fact that the sheets tested have different sizes, since the axial stresses are made, it makes sense to compare the value with a magnitude that is comparable among all; the other reason is the usefulness of this magnitude will take in the future, i.e., applications of this material and its cost will depend directly on the volume of the sheets, which are required for the desired power.

To process the data values refers to the implementation of a high number of tests, it is doing an average of their results, and thus assuming a more varied range of values, in this way it is not canceled imperfections of these values, and making them closer to the what is real in its operation.

Although the power density values are an order of magnitude too low, there is a tendency that depends not only on the thickness of the sheets, as well as the concentration of sodium chloride (electrolyte), to which the sheets are subjected before put into operation.

In Fig.11 is shown that the 0.2mm sheet, under these conditions, demonstrates the best results for all tested electrolyte concentration. The worst case occurs for a sheet of 4mm of thickness, also for all values of concentration of the electrolyte. This value can be explained by the fact that the stresses in this case may not have been high enough, in relation of this sheet dimensions.

As for the concentrations of sodium chloride (electrolyte), it appears that the best values occur for the highest concentration, 20g/L, and the worst cases occur when the concentration is lowest, 5 g/L. With these results could be lead to believe that the higher the concentration of salt, the better the results, but that is not true, since the sheet after a determined value of the electrolyte concentration, approximately 30g /L, enters a state of saturation in respect of its internal loads, which causes a decrease in power density values [16].

Comparing the values obtained in Table II with those of Fig.11 it is noted that the power density generated is greater when greater is the \( P_{\text{mec}} \) exerted on the IPMC.

All values that have been observed previously, have confirmed the values obtained by previous works, including [16], when IPMC are subject to other types of experiments.

C. Second Experimental Step: Axial and Transverse Stresses

Here the procedures of these tests are similar to the first step, but in this case the range of angles of the experimental mechanism, will have different values, 40 °, 50 °, 60 °, 75 ° and 90 °. The values of stress will also be more varied with the following changes in weight and force 344g(3.4N), 544g(5.3N), 755g(7.3N) and 944g(9.3N).

This experimental mechanism will have different operating angles, thereby forming not only axial stresses but also
transverse stress, as seen in Fig 12. These ones stresses have the greatest contribution to power generation.

In earlier tests when only axial forces are made, the thinner sheet showed the best results, so in this step the 0.2mm sheet was the only one to be used in the following experiments.

Since only one was used, values will be analyzed by power densities but unlike the previous step where was considered power values per unit of volume, here will be considered power values per unit of area.

To get an idea of the operation for situations where the electrolyte concentration is less than 5g/L, some tests are also conducted using 1g/L, 2g/L, 3g/L and 4g/L, beyond the concentrations used in the previous section.

A medium angle of 60° was chosen, as shown at Fig.13, and it was tested using the minimum concentrations.

![IPMC](image)

**Fig.13 - IPMC subjected to an inclination of 60°**

It is noted that the value of the power density will be greater, the higher the stress, and as already previously observed, the values develop equally the higher the concentration of the electrolyte, so confirming the results obtained above, and confirming the theoretical model too.

The characteristic values shown at Fig.14 are the result of this, there has been noticed a less contribution on the lower stress situation and more abrupt changes to the higher stress values.

It was concluded that even for values of minimum concentrations the behavior is consistent with the observed values when there are only axial forces applied, although there are higher values. Owing to the fact that in this case there are transverse stresses applied, which will boost the generation of energy, as it is explained in the electromechanical model.

Now all other concentration values higher than those studied above will be tested, for various angles of inclination, and different values of stresses.

Analyzing Fig.15, Fig.16 and Fig.17, starting with the different angles, a common trend is seen for all concentrations, and also for all values of stress, that is an almost linear rise in the power density when the angle also rises. This can be justified by the fact that there are not only axial stresses applied but also transverse too, this one being the main cause of the generation, because IPMC is not only being subjected to an extension force but also a compression force too, that rises when the angle increases.

![Graph 1](image)

**Fig.15 - Results for the second experimental tests : 5g/L.**

![Graph 2](image)

**Fig.16 - Results for the Second experimental tests : 10g/L.**

![Graph 3](image)

**Fig.17 - Results for the second experimental tests : 20g/L.**

Observing now the changes in weight exerted on the sheet, it is observed in earlier works [16] that there are three regions of operation. Only one is studied in this work; the normal operation region, since is in this one that IPMC show a stable behavior.

Thus, stresses studied are in-between, being neither too high nor too low, in order to achieve an approximately linear characteristic of the observed experimental tests. There is a tendency that is common to the three concentrations shown in the previous three figures (Fig.15, Fig.16 and Fig.17), this tendency is also observed in the analysis performed previously when tested minimum concentrations of electrolyte, which is a significant increase in power density generated by the IPMC, as the stress exerted on the IPMC is also increased, confirming what has been explained in the theoretical model.
As previously mentioned when using minimal concentrations of electrolyte, Fig.14, and also the first experimental phase where only axial pressures were applied, Fig.11, this variable has a large influence on the IPMC behavior.

In the case of these three previous figures (Fig.15, Fig.16 and Fig.17), where the IPMC are subject to axial and transverse stresses, due to the different angles and being those imposed stresses from various intensities, a tendency is also observed, which is equal to those found in earlier experimental stages, confirmation one more time that what has previously been deduced from the theoretical model.

Therefore, it is found that the higher the concentration of electrolyte the greater the value of the power density observed. This is true when a maximum value of concentration is not exceeded. Otherwise the IPMC begins to enter a state of saturation, since a great ionic inequality is verified, leading to a loss of energy generation yield from the IPMC.

This scenario is similar to what is described for the variations in weight, thus, also the concentration of electrolyte has a region of normal operation, where IPMC is not saturated, and can then achieve a near linear characteristic. This area may differ from sheet to sheet, depending on the size and materials used, so it is not possible to indicate a standardized value, but in this case, based on work done on [16] it is known that the value for which the saturation region starts is 30g/L.

![Diagram of results](Image)

Based on these three variables observed at Fig.15, Fig.16 and Fig.18 it is concluded that they all contribute to the functioning of IPMC as a generator, and to understand the contributions of these is drawn the diagram on Fig.18.

This diagram is only valid for the normal operation of the IPMC, ie, where it has a stable function. In this situation, the best case results were found, it was when the concentration values of the electrolyte, the inclination angle and value of the stress applied on the sheet, caused by the variation of weight, have their maximum values, at 20g/L, 90° and 944g respectively.

![Diagram of results](Image)

From another point of view, its analyzed the Voltage Variation when stress is applied on the IPMC, Fig.19.

Three distinct situations are considered with different angles, concentrations, and applied stresses, where a higher, lower and an intermediate case are represented.

There are three phases on the voltage variation. The first phase is related to the early 10s, which shows a variation of residual stress due to the residual pressure of the device and container which will hold the weight. As IPMC is already in a closed circuit with the load, it is normal for that to happen, so it will be negligible. Then the axial stress which is the result of weight and consequent force is applied only on the 10s. The second phase is precisely the moment when the mechanical force is applied and sudden change of voltage is seen. As can be seen in more detail in the electrical model of this system, this phase lasts an average of about 10s. Lastly there is the third phase, which is also explained in detail on the electric model. In this phase occurs a small voltage variation with a much higher time interval than in the previous phase, due to diffusion inside the IPMC. The time interval assigned to this phase is the remaining time of the test in these cases it is assumed to be approximately 30 seconds.

In Table III is observed the fast and slow time constants of Fig.19. Thus can be seen the gap in values between the first voltage change that occurs between 10s up to 20s, which is characterized by a fast time constant, and the second voltage change that occurs approximately between 20s and 50s, which is characterized by a slow time constant. This constant which can be seen in the situation of 5g/L of electrolyte, is 11 times smaller than its respective fast time constant.

![Voltage variation when force is applied](Image)

**TABLE III**

<table>
<thead>
<tr>
<th>Fast and Slow Time Constants on the Voltage Variation.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time Constants</strong></td>
</tr>
<tr>
<td>(10s to 20s)</td>
</tr>
<tr>
<td>20g/L; 90°; 3.85×10⁶ N/m²</td>
</tr>
<tr>
<td>10g/L; 60°; 3.04×10⁶ N/m²</td>
</tr>
<tr>
<td>5g/L; 40°; 1.40×10⁵ N/m²</td>
</tr>
</tbody>
</table>

So the existence of two important time intervals are seen, also observed in [16], that characterize the IPMC by their time constants.

An energy analysis was performed. Starting with the functional origin of experimental tests which aim to recreate real life conditions of an IPMC generator at the elbow of a human being, thus allowing the conversion of mechanical energy to electrical energy, using the movements of the human
Typically the movement that occurs at the elbow is driven by the movement of the legs, i.e. when a human is walking or running he uses the rocking arm for the drive and up to the equilibrium of the body. Thus, the tilt angles that the piece is subjected during the experimental tests will be related to a particular time value.

It is assumed the arm movement, from 0° to 90°, when a human is walking is approximately 2s. Thus is achieved angles relate to a time value in the Table IV.

<table>
<thead>
<tr>
<th>Angles [°]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.89</td>
</tr>
<tr>
<td>50</td>
<td>1.11</td>
</tr>
<tr>
<td>60</td>
<td>1.33</td>
</tr>
<tr>
<td>75</td>
<td>1.67</td>
</tr>
<tr>
<td>90</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Now with these values and the corresponding values of the results presented above of power density for each concentration of electrolyte and weights recorded, it is possible to calculate the values for energy, using the following expression.

\[ E = \int P \, dt \] (14)

Fig.20 represents a compiling of the values of energy density due to the force, for the various concentrations. There is an increasing trend, similar to those observed above for power densities where the intensities rise as the variations in weight, which is responsible for stresses. For the two higher concentrations, there is an abrupt increase when switched from a force of 7.3N to 9.3N. There is also an increasing tendency and greater stress to the final values when the concentration of the electrolyte increases.

Thus it is safe to conclude that as the power, energy is directly proportional to the value of the concentration of the electrolyte and the weight value which generates stresses on IPMC.

Fig.20 - Energy Density generated.

### D. Comparing Results

The analysis made earlier took into account only the average values of power density values obtained, as explained, it was the most realistic method of presenting the results. When it is desired to compare the values with values from the literature it is the maximum value experienced, in order to get an idea of the mechanism potential in accordance with absolute values.

Thus the maximum value observed for the power generated in this work was 667.7nW, which corresponds to a value of a power density of 6.32nW/cm³. This value was obtained for a situation in which the angle was 90°, a concentration of 20g/L and the variation in weight is greater, i.e. the situation where the average values are also the maximum. With this value it is possible to compare it with some maximum values obtained in previous works, in Table V.

<table>
<thead>
<tr>
<th>Works with IPMC materials</th>
<th>Power density [nW/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Costa [16]</td>
<td>610.1</td>
</tr>
<tr>
<td>S.V.Anand [10]</td>
<td>91.25</td>
</tr>
<tr>
<td>J. Bruflau Penella [17]</td>
<td>2.02</td>
</tr>
<tr>
<td>Giacomello [21]</td>
<td>1.40</td>
</tr>
</tbody>
</table>

However, although these studies are performed with the same material, they cannot be comparable due to its experiments characteristics, once the experimental mechanism is different. In most cases stresses are applied in specific regions of the IPMC, or compressed using the entire surface [16]. As noted previously in the case of this study, IPMC is under axial and transverse stresses but due to the extension and not to compression, which is a completely innovative procedure, for the studies conducted to date.

There is another group of material that it is important to refer to, namely the piezoelectric materials. Observing two kinds of it, the PZT (Lead Zirconate Titanate) and PVDF (Polivinilidene Difluoride). The first are ceramic, revealing little flexibility, which is one of its main drawbacks, being confined to a small range of uses. The second are polymers, which show greater flexibility and a greater resemblance to the IPMC materials, in terms of their utilization.

Since for comparing the values of a material it is suitable to have the same characteristics in terms of utilization, it is assumed the application of a piezoelectric material (PVDF) in the elbow of a human arm, i.e., making the same motion as described this work and then it will be compared the values obtained.

Based on what is found in [23, 25], these materials have values in the range of 100μW/cm³, so that is a large gap compared with the best value observed in this work, due to the nature of the stress made. But still is considered the opportunity to create specific conditions to adapt a IPMC on human elbow and estimate how much it could generate, comparing with the range of values of the PVDF material.

Starting with the dimensions are assumed the values in Table VI.

<table>
<thead>
<tr>
<th>Length [cm]</th>
<th>Width [cm]</th>
<th>Thickness [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.00</td>
<td>2.00</td>
<td>0.02</td>
</tr>
</tbody>
</table>

With this we reached the volume of 1cm³, which will be
used to calculate the power density on the power value of 667.7nW, having been previously mentioned as being the maximum value observed. It takes the value of power density, which has the value 0.67µW/cm².

But as seen in [16] the use of other types of electrolyte causes a boost of generated values, so it's considered that instead of water with sodium chloride (NaCl) an electrolyte made of propylene as solvent and lithium ion (Li^+) used as the solute. Thus, in this reference is seen that the increase in power density is around 300%, and applying this to the value found for increased power density, we get the value of 2.68µW/cm².

Therefore, if piling IPMC parts in order to boost the generated value, it is concluded that if we have 30 IPMC on parallel, it will reach a value of 80µW/cm², this structure have a maximum thickness of only 0.6cm.

It was concluded that at best, and in optimal conditions, a mechanism of these on the human elbow as an harvesting device can generate, on impulse, up to 80µW/cm² without bringing discomfort to its user.

IV. CONCLUSION

In this work was explored the functional characterization of a electromechanical device, which uses artificial muscles (IPMC - Ionic Polymer Metal Composite) as electromechanical transducers, when subjected to axial and transverse stresses.

In order to validate the device's model a large number of practical experiment were conducted and from them results were presented. The good correlation between theoretical model predictions and experimental results revealed the usefulness of the model developed. So based on that it is conclude this electromechanical device works as a energy harvesting system. And eventually may even be applied in a real situation, using the movement of human locomotion or biological movements to generate electric energy.

REFERENCES