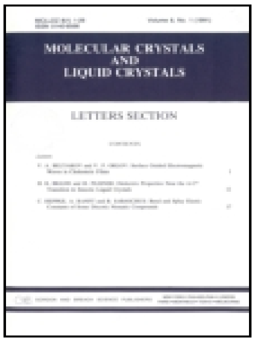
MOLECULAR CRYSTALS AND LIQUID CRYSTALS

LETTERS SECTION

Molecular Crystals and Liquid Crystals

ISSN: 1542-1406 (Print) 1563-5287 (Online) Journal homepage: http://www.tandfonline.com/loi/gmcl20

Theoretical modeling of power harvested by piezo-cellular polymers

C. Ennawaoui, A. Hajjaji, A. Azim & Y. Boughaleb

To cite this article: C. Ennawaoui, A. Hajjaji, A. Azim & Y. Boughaleb (2016) Theoretical modeling of power harvested by piezo-cellular polymers, Molecular Crystals and Liquid Crystals, 628:1, 49-54, DOI: 10.1080/15421406.2015.1137679

To link to this article: http://dx.doi.org/10.1080/15421406.2015.1137679

MOL. CRYST. LIQ. CRYST.
2016, VOL. 628, 49–54
http://dx.doi.org/10.1080/15421406.2015.1137679

Theoretical modeling of power harvested by piezo-cellular polymers

C. Ennawaoui, A. Hajjaji, A. Azim, and Y. Boughaleb

Laboratory of Engineer Science for Energy, National Engineering School of Applied Sciences, Chouaïb Doukkali University, El Jadida, Morocco

ABSTRACT
In recent years, piezoelectric polymers have been widely used as smart materials. Electromechanical applications are currently focused on energy harvesting, including the development of autonomous device and modeling the power can be harvested by using this materials. The topic of this paper is studying the most important properties of piezo-cellular polymers in energy harvesting. The aim presents a theoretical model of the power harvested by using the piezo-cellular polymers. The theoretical model allows to determinate the power density based on cell morphology, thickness, the dielectric constant and the other factors.

KEYWORDS
Piezoelectric polymers; energy harvesting; piezo-cellular polymers; theoretical model; power harvested

Introduction

Energy harvesting is considered as the center of human's attention from a long time ago and still have the same importance. There are different and many of types of sources on one hand those with a large scale and on the other hand the weak and diffuse sources of energy in our environment these last ones occupy an important part of the last studies because this harvesting energy face the problem of batteries size and weight [1], and who are replaced periodically by many solutions. From these sources, the energy harvesting can be executed through numerous methods, such as electromagnetic induction [2], electrostatic generation [3], electrostrictive [4–6] and piezoelectric materials [7]. Contemporary studies clarified the prospect of harvesting energy using piezoelectric polymers [8]. There are diver polymer categories that can be considered as piezoelectric. The bulk polymers [7] take place on the top of the categories of the piezoelectric polymers which are solid polymer films that characterized the piezoelectric mechanism through their molecular structure and its arrangement. The piezoelectric composite polymer [9] took the second category. These are polymer structures with integrated piezoelectric ceramics hence the piezoelectric effect is generated. These composites make use of the mechanical flexibility of polymers and the high electromechanical coupling of the piezoelectric ceramics. And finally the last type that is a totally different of piezoelectric polymer than the first two categories is the piezo-cellular polymers [10] (Figure 1).

Films with cellular or porous structure represent a new family of piezoelectric polymer and are the subject of our work. In order to develop other types of polymeric materials with a higher piezoelectric activity and a wide range of properties and by reducing at the

CONTACT C. Ennawaoui chouaib.enna@gmail.com; A. Hajjaji hajjaji12@gmail.com
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gmcl.

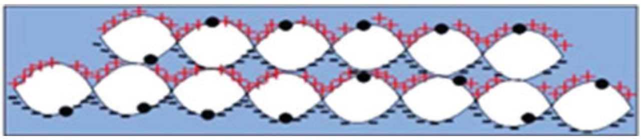

Figure 1. The piezo-cellular polymers.

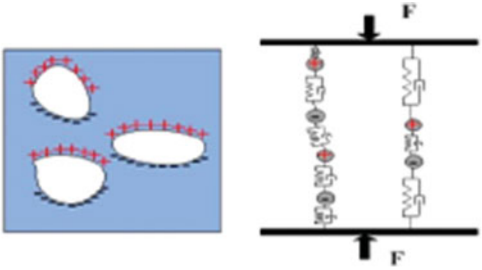

Figure 2. Macro-polarized dipole support of a piezo-cellular material.

same time the cost, Gerhard Sessler was the first one who invented this structure in the early 1960s [11], he decided to develop a charged polymer device so that can be used as a microphone. It was only viewed and named as 'space charged electrets'. It wasn't accepted until the late 1980s, the researchers considered the concept of treating the space charged electrets as a 'black box' and investigated the piezo and pyroelectricity of those films [12]. When the polymer surfaces enclosing voids are charged, the charged polymer canceled operate as a piezoelectric material, coupling electrical energy and mechanical energy. Structures like that can have a piezoelectric coefficient and can even reach up to 20,000pC/N [13], a similar value greater than that of the piezoceramic.

Electrical study of piezo-cellular polymers

Harvesting energy is simply made by a resistive load and not a technique developed for energy harvesting.

In the literature [14], the systems of equations that govern the piezoelectric mode 33 (Figure 3) are:

$$S_3 = d_{33}.E_3 + s_{33}{}^{E}.T_3 \tag{1}$$

$$D_3 = \varepsilon_{33}{}^{T}.E_3 + d_{33}.T_3 \tag{2}$$

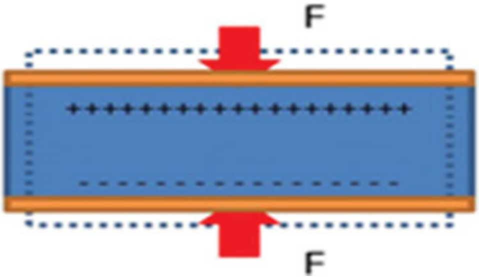

Figure 3. Piezoelectric Mode " 33 ".

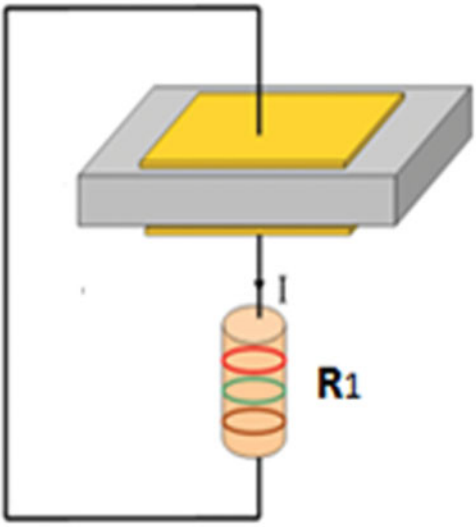

Figure 4. Electrical model.

where S, T, D and E are strain, stress, electrical displacement and electric field, respectively. The dielectric permittivity, ε^T, indicates the charge stored in the capacitive element of the piezoelectric material at constant stress. The piezoelectric coefficient, *d*, is the electromechanical coupling term. The compliance, s^E, relates stress and strain at constant electric field.

The expression of T stress in function of the strain S is given by:

$$T3 = \frac{\mathrm{S}_3 - \mathrm{d}_{33}.\mathrm{E}_3}{\mathrm{S}_{33}} \tag{3}$$

So it is possible to express the electric displacement D as a function of the field E:

$$D_3 = \varepsilon_{33}^T E_3 + d_{33}\frac{S_3 - d_{33}E_3}{s_{33}}$$

The purpose of this part is to model the current generated by the piezoelectric material with the use of a purely resistive load as shown in figure 4.

The total electric field is equal to the alternating electric field ER across the resistor R1;

After applying the mesh law: $\mathrm{E}_3 = \mathrm{E}_\mathrm{R}$

Therefore

$$\frac{\partial E_3}{\partial t} = \frac{\partial E_r}{\partial t}$$

The electric field at R_1 edge is given by

$$E_r = -\frac{R_1 I}{e}$$

Then the current is expressed in the form:

$$I = A\frac{\partial D_3}{\partial t} = A\left[\varepsilon_{33} - (d_{\downarrow 33}/s_{\downarrow 33})\right]\frac{\partial E_{\downarrow 3}}{\partial t} + \frac{d_{\downarrow 33}}{s_{33}}\frac{\partial S_{\downarrow 3}}{\partial t}$$

With A being the active surface of the polymer

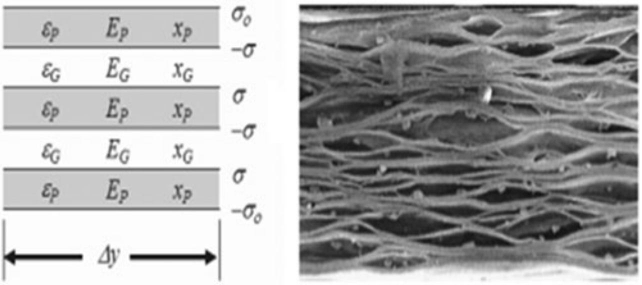

Figure 5. Schematic model of the piezo-cellular film.

The general expression the current I is :

$$I = A\left[\frac{\left(-\varepsilon_{33}+\frac{d_{33}^2}{s_{33}}\right)R_1}{e}\right]\frac{\partial I}{\partial t}+\frac{d_{33}}{s_{33}}\frac{\partial S_3}{\partial t}$$

The objective is to take the expression of the power dissipated in the resistive load, based on the equation that links the power, current and load.

$$P = R_1 I^2$$

So the maximum current from the polymer in the case of mechanical stress (from modeling performed previously) is expressed in the form:

$$\left|I_{\downarrow}\,\mathrm{max}\right| = \left|((d_{\downarrow}33)/s_{\downarrow}33\ j.w.A.S_{\downarrow}M)/\left(1+\left(\varepsilon_{\downarrow}33-\left([\![d^2]\!]_{\downarrow}33\right)/s_{\downarrow}33\right)R_{\downarrow}1/e.j.w.A\right)\right|$$

So the power dissipated in the resistor R_1 is expressed in the equation:

$$P = \frac{\mathrm{R}_1}{2}\cdot\frac{\left(\frac{d_{33}}{s_{33}}.w.A.S_M\right)^2}{1+\left[\left(\varepsilon_{33}-\frac{d_{33}^2}{s_{33}}\right)\frac{R_1}{e}.w.a\right]^2}$$

The cellular film is modeled as a layered structure made of a gas of alternating layers of polymer and which are electrically charged at their interfaces (figure 5).

The expression of the piezoelectric constant developed in literature and the development of a model of the power harvested by piezo-cellular polymer that is able to show the influence of the porosity on the power harvested. Simplified equation of the piezoelectric constant in piezo-cellular polymers by Arvelo. J. I and al.2010 [16]

$$d_{33} = \frac{\sigma_G}{Y}.\left[\frac{R.(1+V)}{(R+V)^2}\right]$$

We set the relationship of porosity:

$$V = \frac{X_G}{X_P}$$

where Xg and Xp are the thicknesses of the void and the polymer, respectively. The relationship of the dielectric constant is given by

$$R = \frac{\varepsilon_G}{\varepsilon_p}$$

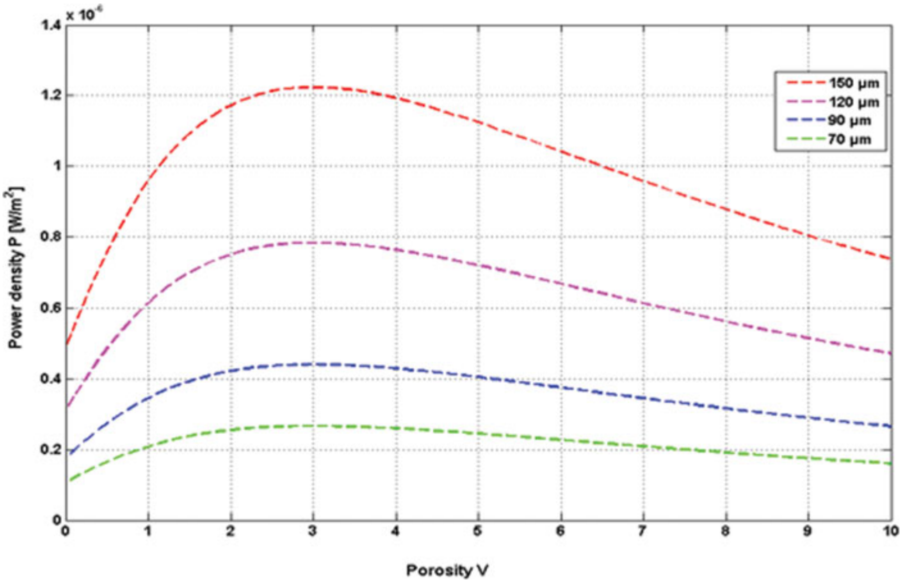

Figure 6. Power harvested by piezo-cellular films of polypropylene.

Therefore:

$$P = \frac{R_1}{2} \cdot \frac{\left(\frac{\frac{\sigma_G}{Y}\cdot\left[\frac{R.(1+V)}{(R+V)^2}\right]}{s_{33}}.\omega.A.S_M\right)^2}{1+\left[\left(\varepsilon_{33}-\frac{\left(\frac{\sigma_G}{Y}\right)^2\cdot\left[\frac{R.(1+V)}{(R+V)^2}\right]^2}{s_{33}}\right)\frac{R_1}{e}.\omega.a\right]^2}$$

The relationship between the Young's modulus and complacency is given by

$$S_{33} = \frac{1}{Y}.$$

After simplifications, the expression for the power becomes as follows

$$P = 2\pi^2 R_1 \frac{\left(\sigma_G.\left[\frac{R.\,(1+V)}{(R+V)^2}\right].f.A.S_M\right)^2}{1+4\pi^2\left(\varepsilon_{33}-\sigma_G^2.\left[\frac{R.\,(1+V)}{(R+V)^2}\right]^2\right)^2\left(\frac{R_1}{e}.f.A\right)^2}$$

To determine the value of the permittivity ε_{33} of the film, we used the BURGGMAN law [17].

Figure 6 presents the theoretical results obtained with piezo-cellular films of polypropylene and characterized by [0.10] in porosity and having various thicknesses (70, 90, 120, and 150 µm). The main theoretical results show that the power density increases with rising the fraction of porosity, up to a critical limit which the power density decreases. Beyond such a limit, the pores coalesce and the film loses its pores, and therefore loses the local dipoles responsible for the piezoelectricity.

Conclusion

In this study the proposed model gives a general idea about the parameters that directly influence the power harvested by a resistive load in piezo-cellular polymers. The expression of power density was established using the fundamental equations of piezoelectricity, the power based on electrical parameters and the relation of the piezoelectric constant in a porous medium. Our study shows that the harvested power increases with the fraction of porosity up to a limit value that depends on the film thickness.

Future work will focus on improving the performance of the harvested power by developing new systems and using hybridization with other materials.

References

[1] Priya, S. (2007). *J. Electroceramics*, *19*(1), 167–184.

[2] Williams, C. B., Shearwood, C., Harradine, M. A., Mellor, P. H., Birch, T. S., & Yates, R. B. (2001). *Proceed. IEEE*, *148*(6), 337–342.

[3] Mitcheson, P. D., Green, T. C., Yeatman, E. M., & Holmes, A. S. (2004). *J. Microelectrom. Systems*, *13*(3), 429–440.

[4] Belhora, F., Cottinet, P.-A., & Guyomar, D. (2012). *Sensors and Actuators*, *183*, 50–56.

[5] Meddad, M., Eddiai, A., & Guyomar, D. (2012). *J. Appl. Phys.*, *112*(5), 054109.

[6] Eddiai, A., Meddad, M., & Guyomar, D. (2012). *Synt. Mel.*, *162*(21–22), 1948–1953.

[7] Harrison, J. S., & Ounaies, Z. (2002). Piezoelectric polymers, *Encyclopedia of Polymer Science and Technology*, Wiley, New York, pp. 474–98.

[8] Sameoto, K. S., Ramadan, D., & Evoy, S. (2014). *Smart Materials and Structures*, *23*(3).

[9] Levassort, F., Lethiecq, M., & Desmare, R. (1999). *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, *46*, 1028–34.

[10] Hillenbrand, J., & Sessler, G. M. (2004). *IEEE Trans. Dielectr. Electr. Insul.*, *11*, 72–9.

[11] Sessler, G., & West, J. (1962). *Acoustical Society of America*, *34*, 1787–8.

[12] Bauer, S., Gerhard-Multhaupt, R., & Sessler, G. M. (2004). *Physics Today*, *57*, 37–43.

[13] Gerhard Multhaupt, R. (2002). *IEEE Trans. Dielectrics and Electrical Insulation*, 850–859.

[14] Qaiss, A., Saidi, H., Fassi-Fehri, O., & Bousmina, M. (2013). *Polymer Engineering and Science*, *53*(1), 105–111.

[15] Wegener, M., Tuncer, E., Wirges, W., Gerhard Multhaupt, R., Dansachmuller, M., BauerGogonea, S., Schwodiauer, R., & Bauer, S. (2004). *IEEE Ultrasonics Symp*. (Piscataway, NJ: IEEE), 1138.

[16] Arvelo, J. I., Busch-Vishniac, I. J., & West, J. E. (2010). *Johns Hopkins Apl. Technical Digest*, *28*(3), 262–263.

[17] Mandin, Ph., & Ait Aissa, A. (2007). *Chemical Engineering and Processing*, *47*(11), 1926–1932.