Materials Research Bulletin 74 (2016) 50–56

Contents lists available at ScienceDirect

Materials Research Bulletin

journal homepage: www.elsevier.com/locate/matresbu

Electrostatic induction power generator using hydroxyapatite ceramic electrets

Norio Wada[a,*], Naohiro Horiuchi[a], Kastuyuki Mukougawa[a,b], Kosuke Nozaki[a], Miho Nakamura[a], Akiko Nagai[a], Toshinori Okura[b], Kimihiro Yamashita[a]

[a] *Department of Inorganic Materials, Institute of Biomaterials and Bioengineering, Tokyo Medical and Dental University, 2-3-10 Kanda-Surugadai, Chiyoda, Tokyo 101-0062, Japan*
[b] *Department of Environmental and Energy Chemistry, Kogakuin University, 2665-1 Nakanocho, Hachioji, Tokyo 192-0015, Japan*

ARTICLE INFO

Article history:
Received 22 April 2015
Received in revised form 2 September 2015
Accepted 6 October 2015
Available online xxx

Keywords:
A. Ceramics
C. Infrared spectroscopy
D. Dielectrics
D. Electrical properties
D. Energy storage

ABSTRACT

In this paper, we examine the power generation performance of a rotational electret power generator theoretically and experimentally using electrostatic induction based on the properties of hydroxyapatite (HAp) ceramic electrets; the two surfaces of the electrets have opposing polarities. The HAp electrets have long-term stability in comparison with polymer electrets, which are more commonly used. The theoretical power output is proportional to the square of the total surface area of electrets per block of the stator, frequency of the rotor, and surface electric potential of the electret. Moreover, the power output is proportional to the square of the inverse of the air gap between the rotor and electrets. The behavior of power outputs obtained under different experimental conditions correlated with our theoretical prediction. The maximum output power generated by our prototype electret generator was 3.6 μW with the frequency of the rotor being 24 Hz.

1. Introduction

Electrets are dielectric materials with a quasi-permanent charge trapped inside, which generates a strong electrostatic field around it, and are one of the indispensable components of electrostatic transducers such as microphones and power generators [1–3]. Eguch first developed a carnauba wax electret using a thermal polarization method [4]. The charge in the carnauba wax is known to be stable. The electret generator is an apparatus that transforms mechanical energy into electrical energy through the medium of the electric field generated by the electrets. Electrostatic induction using electrets is then adopted as the principle for power generation, and this power generation method is attracting much attention. Electrostatic generators differ from electromagnetic generators in that electromotive force is purely electric. Electromagnetic induction requires complicated three-dimensional structures for coils. In addition, extremely high frequency is required to obtain sufficient output voltage. On the other hand, electrostatic induction has desirable features such as simple structure, and at a low frequency range, electrostatic power generators have higher performance than electromagnetic power generators. For these reasons, we employed electrostatic induction using a ceramic electret for power generation because of their electric performance, such as high power outputs in small scale and simple structure. Electret generator theory and experiments were first reported by Jefimenko et al. [5]. Theories and experiments of electret generators have since been reported by several researchers [2,3,6,7]. Polymer films with a mono-polarity have been used as electrets in most of the published studies on electret power generators, because polymer electrets have high surface charge densities and their thickness can be reduced [3]. In addition, the obtained power outputs were a few tens of μW, and the surface charge density decreased with time; that is, its long-term stability is of concern [2,3,5,6]. The crucial issue for improved polymer electret properties is the maintenance of surface charge density for increased lifetime of the device. As an example, the surface charge density of a perfluorinated polymer electret loses half its value after 100 h [3].

Hydroxyapatite (HAp; $Ca_{10}(PO_4)_6(OH)_2$) is one of the most common biocompatible materials [8]. Yamashita et al. discovered that HAp works as a proton conductor and can be polarized with an external electric field at elevated temperatures and it maintains this polarized state; that is, these materials can become electrets and also indicated that polarization takes place in HAp due to rotations and displacements of the protons that are destabilized with thermal vibration [9,10]. The investigations with HAp

---

[*] Corresponding author. Fax: +81 03 5280 8015.
E-mail address: nwada.bcr@tmd.ac.jp (N. Wada).

http://dx.doi.org/10.1016/j.materresbull.2015.10.007

electrets have been carried out in such areas as the crystal growth of biomaterials and the behaviors of cells and microbes [10–16].

In addition, the HAp ceramic electrets have several tens of voltage of surface electric potential, several decades as lifetime, and the two surfaces being of opposing polarities [17–19]. We recently studied the fundamental electrical properties of the HAp electret using Kelvin probe method and reported that the surface electric potential is proportional to the surface charge density attributable to the electrets and the surface electric potential attributable to several overlapping electrets is given by the algebraic sum of the surface electric potentials of individual electrets [20]. These properties of HAp electrets are advantageous to the performance improvements of power generation in comparison with polymer electrets, which are most commonly used. We believe that the HAp ceramic electrets with a long-term stability are useful for the power generators instead of the polymer electrets with a short lifetime.

In the present study, we examine the power generation performance of a prototype generator using electrostatic induction based on properties of HAp ceramic electrets. The surface electric potential of the HAp ceramic electrets is smaller than that of polymer electrets, but the stability of surface charge densities is higher.

2. Theoretical approach to a rotational electret power generator

The rotational power generator based on electrostatic induction consists of a rotor electrode and a stator electrode with ceramic electrets, and there is an air gap between these electrodes, as shown in Fig. 1. The simplified model of the power generator, as shown in Fig. 1a, defines the pole number of the power generator as 4, indicating a 4-pole stator and a 4-pole rotor. The one pole of the stator consists of two blocks with electrets having opposite polarity. The polarity of the electrets on the stator alternates, as shown Fig. 1a. The multi-pole stator and rotor are shaped like a fan. The cross section of the main part of the power generator is shown in Fig. 1b. According to electromagnetic theory, we estimated the output power of an electret power generator with pole number n and the current in the load resistance by using a simple capacitance model as follows [5].

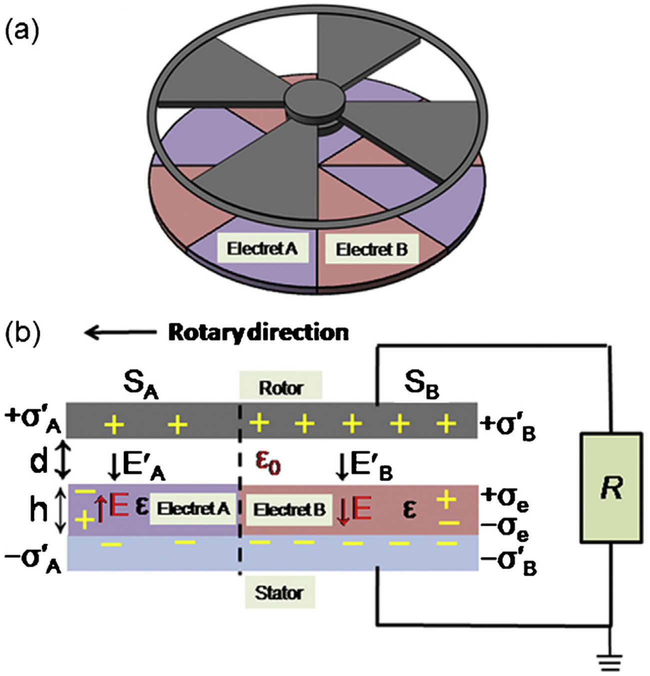

Fig. 1. (a) Schematic representation of the rotor and stator of with pole number 4. (b) Schematic representation of a cross section of the parallel-plate capacitor with electrets between its plates.

We consider a parallel-plate capacitor containing electrets in the space between their plates as a stator and a rotor, as shown in Fig. 1b. Let the thickness of the electrets A and B be h, and the gap between the electret and the rotor be d. The left part has the magnitude of an electric field E directed upward and the right part has the magnitude of an electric field E directed downward. The surface area per block of the rotor is S, and the surface areas of the electrets A and B are S_A and S_B, respectively, as shown in Fig. 1b. The relationship between these surface areas is $S = S_A + S_B$. The surface charge densities induced on the surface of the rotor and the stator with surface area S_A, are $+\sigma'_A$ and $-\sigma'_A$, and the densities associated with surface area S_B, are $+\sigma'_B$ and $-\sigma'_B$, respectively. The surface charge densities on the electrets A and B are $\pm\sigma_e$. We assume that the electric field in the capacitor is directed downwards, and the electric fields outside the electret A and B are E'_A and E'_B, respectively. The load resistance is R and the output voltage and current are V and I. The permittivity constants of the air gap, and of the electrets A and B are ε_0,ε, and ε, respectively.

Assume the rotor moves from right to left. Applying Kirchhoff's second low in the left part (A part) of the capacitor, we have

$$V = E'_A d + E_A h, \tag{1}$$

and in the right part (B part) of the capacitor

$$V = E'_B d + E_B h, \tag{2}$$

Applying Gauss's law to the field (the A part) including the air gap and the electret A, and the electret A and the stator electrode under the A part of the stator, we have

$$S_A E'_A = \frac{S_A \sigma'_A}{\varepsilon_0}, \text{namely}, E'_A = \frac{\sigma'_A}{\varepsilon_0}, \tag{3}$$

and

$$S_A E_A = S_A \frac{(\sigma_e - \sigma'_A)}{\varepsilon}, \text{namely}, E_A = \frac{(\sigma_e - \sigma'_A)}{\varepsilon}. \tag{4}$$

Substituting (3) and (4) into (1), we obtain

$$V = \sigma'_A \left(\frac{d}{\varepsilon_0} + \frac{h}{\varepsilon} \right) - \frac{\sigma_e h}{\varepsilon}, \text{namely}, \sigma'_A = \frac{(V\varepsilon_0\varepsilon + \sigma_e h)}{\varepsilon d + \varepsilon_0 h}. \tag{5}$$

Then, the charge $Q_A = S_A \sigma'_A$ on the left side of the upper plate is

$$Q_A = S_A \sigma'_A = \frac{(V\varepsilon_0\varepsilon + \varepsilon_0 \sigma_e h) S_A}{(\varepsilon d + \varepsilon_0 h)}. \tag{6}$$

A similar calculation for the right part yields

$$Q_B = S_B \sigma'_B = \frac{(V\varepsilon_0\varepsilon - \varepsilon_0 \sigma_e h) S_B}{\varepsilon d + \varepsilon_0 h}. \tag{7}$$

The total charge $Q = Q_A + Q_B$ on the upper plate of the capacitor is therefore

$$Q = \frac{V(\varepsilon_0\varepsilon)S}{(\varepsilon d + \varepsilon_0 \sigma_e h)(S_B - S_A)/(\varepsilon d + \varepsilon_0 h)}, \tag{8}$$

where $S = S_A + S_B$ is the surface area of the upper plate. Since the capacitance of the capacitor is

$$C = \frac{\varepsilon_0 \varepsilon S}{\varepsilon d + \varepsilon_0 h}, \tag{9}$$

we can rewrite as

$$Q = \frac{CV + (\varepsilon_0 \sigma_e h)(S_B - S_A)}{(\varepsilon d + \varepsilon_0 h)}. \tag{10}$$