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Performance enhancement of cylindrical ferroelectric transducers

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Abstract

In this paper, the feasibility of using ferroelectric materials as a thermal transducer based on electrocaloric effect (ECE) has been studied. The electrocaloric response of the ferroelectric capacitor PMN-25PT which is a ceramic with the formula of $0.75Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.25PbTiO_3$ and the dynamics of temperature variations at the inner boundary of a cylindrical sample to an applied periodic electric field have been studied. Alternative switching of the electrocaloric element allow the generation of directed heat flux. At first the outer boundary of the sample is put in convection condition and then in constant temperature condition. Inner boundary is insulated in two cases. Results show that different boundary conditions affect the transducer performance.

Keywords: Electrocaloric effect; Ferroelectric; Micro heat pump; Transducer

1. Introduction

In the recent years, the new ferroelectric heat pump and transducer using dielectric materials has been a center of attention for the researchers. Electrocaloric effect is the physical phenomenon that occurs in ferroelectric materials which change their temperature under applied electric field. When electric field in the sample changes periodically, heat is released or absorbed due to electrocaloric effect in a periodic manner as well [1]. In other words, the exchanged heat is a function of the applied electric field. Indeed, the pyroelectric and electrocaloric effects may be considered as direct and inverse electrothermal conversion. The ECE effect may be used for heat transducer/refrigeration whereas the pyroelectric effect may be used in temperature/heat sensors or energy harvesting devices [2]. Energy conversion and electrocaloric effect have been actively studied in recent years with the aim of developing effective generators or cooling devices [3–6]. Some simulation studies have been performed such as those in Refs. [7–12]. Electrocaloric and pyroelectric effects are connected with the temperature dependence of induced polarization. A theoretical description of the thermopolarization effect was presented in Ref. [13], where it was shown that the appearance of polarization is proportional to the temperature gradient. An opposite effect can be assumed, that appearance of a heat flux in the dielectric being proportional to the rate of polarization variations. Also, the relation of the electrocaloric effect to the remnant and induced polarization of a dielectric was studied by Marvan et al. [1]. The induced electric polarization by an external bias electric field plays a role similar to spontaneous polarization. The electrocaloric effect is coupled with induced polarisation by an AC electric field [14,15]. Thus, to obtain a considerable ferroelectric transducer an effective thermodynamic cycle as well as the considerable magnitude of the electrocaloric effect is needed. This paper shows how these parameters contribute to the heat flux in a cylindrical sample. The simulation results for a physical model of the ferroelectric material under application of a periodic electric field are presented.

2. Thermodynamics of the electrocaloric elements

The thermodynamic equation of a ferroelectric material may be written as:

$$U = W_e + W_m + Q \quad (1)$$

where U, W_e, W_m and Q are the internal, electrical, mechanical and thermal energy, respectively. Since no stress is applied to the sample the term of mechanical energy from (1) is neglected.

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The electrical energy can be written as:

$$dW_e = EdD \tag{2}$$

where E is the electric field and D the electric displacement induction. D is a function of E and temperature T and then it can be written as:

$$dD = \frac{\partial D}{\partial E}dE + \frac{\partial D}{\partial T}dT \tag{3}$$

From (1), the variations of internal energy is given by

$$dU = dW_e + dQ = \frac{\partial U}{\partial E}dE + \frac{\partial U}{\partial T}dT \tag{4}$$

Replacing the expression of the electrical energy into the (4) gives the heat variations as:

$$dQ = \left(\frac{\partial U}{\partial E} - E\frac{\partial D}{\partial E}\right)dE + \left(\frac{\partial U}{\partial T} - E\frac{\partial D}{\partial T}\right)dT \tag{5}$$

The entropy S is given by

$$dS = \frac{dQ}{T} = \frac{1}{T}\left(\frac{\partial U}{\partial E} - E\frac{\partial D}{\partial E}\right)dE + \frac{1}{T}\left(\frac{\partial U}{\partial T} - E\frac{\partial D}{\partial T}\right)dT = MdE + NdT \tag{6}$$

where

$$M = \frac{1}{T}\left(\frac{\partial U}{\partial E} - E\frac{\partial D}{\partial E}\right) \quad N = \frac{1}{T}\left(\frac{\partial U}{\partial T} - E\frac{\partial D}{\partial T}\right) \tag{7}$$

It is an exact differential then

$$\frac{\partial M}{\partial T} = \frac{\partial N}{\partial E} \tag{8}$$

From this we have:

$$\left(\frac{\partial U}{\partial E} - E\frac{\partial D}{\partial E}\right) = T\frac{\partial D}{\partial T} \tag{9}$$

By replacing (9) in (5) and assuming that in any case

$$\frac{\partial U}{\partial T} = c \gg E\frac{\partial D}{\partial T} \tag{10}$$

where c is the thermal capacitance [16]. The expression of dQ simplified to

$$dQ = T\frac{\partial D}{\partial T}dE + cdT \tag{11}$$

Upon the application of an electric field, the exchanged heat will be given by the integration of (11).

The two distinct effects of pyroelectric and electrocaloric come from the equation of electric displacement as

$$D = D_r + \varepsilon E \tag{12}$$

where D_r is the remnant electric displacement and ε is the dielectric permittivity. As for a ferroelectric material $D \approx P$ [16], (12) can be written as

$$P = P_r + \varepsilon E \tag{13}$$

where P is the polarization and P_r is the remnant polarization. Writing the differential of the induction and replacing it into (11) leads to

$$dQ = T\left(\frac{\partial P_r}{\partial T} + E\frac{\partial \varepsilon}{\partial T}\right)dE + cdT \tag{14}$$

The term of $T(\partial P_r/\partial T + E\,\partial\varepsilon/\partial T)dE$ determines the quantity of heat released (or absorbed) by a thermal electrocaloric source (EC element). The first term in the parenthesis is known as the pyroelectric effect, whereas the second one is known as the electrocaloric effect. In the following numerical simulations, the transducer is simply modeled as the following

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\left(\frac{\partial^2 T}{\partial r^2} + \frac{\partial T}{r\partial r}\right) - \frac{T}{\rho c}\left(\frac{\partial P_r}{\partial T} + E\frac{\partial \varepsilon}{\partial T}\right)\frac{dE}{dt} \quad R_{in} < r < R_{out} \tag{15}$$

3. Numerical procedure

The sample in Fig. 1 presents a simple physical model, which was used to describe the cylindrical ferroelectric transducer based on ECE. We will only consider the temperature variations along the radial axis. In this case, the temperature distribution $T(r, t)$ along the radial coordinate can be found by solution of (15) which satisfies the following initial and boundary conditions:

1) $T_{t=0} = 300$ K, $\quad \frac{\partial T}{\partial r}\big|_{r=R_{in}} = 0\ K/m, \quad -k\frac{\partial T}{\partial r}\big|_{r=R_{out}} = h(T - 300)$
2) $T_{t=0} = 300$ K, $\quad \frac{\partial T}{\partial r}\big|_{r=R_{in}} = 0\ K/m, \quad T_{r=R_{out}} = 300$ K

One boundary ($r = R_{in}$) is thermally insulated (i.e. heat flux at this point was absent), whereas the outer boundary, at first is put in convection condition and then it put in constant temperature of 300 K. We have chosen the PMN-25PT material whose dielectric constant is rather sensitive to temperature variations. Its physical characteristics are specified in Table 1. The values of $\partial P_r/\partial T$ and $\partial\varepsilon/\partial T$ for PMN-25PT have been calculated from the experimental results shown in Fig. 2a and b as: $\partial P_r/\partial T = -2.68 \times 10^{-3}\ C/(m^2\ K)$ and $\partial\varepsilon/\partial T = 1.8 \times 10^{-9}\ C/(m^3\ \text{V}\ K)$. The thermal capacitance c and thermal conductivity k are assumed to be constant. The numerical simulation of the transducer or the model (15) was performed using the finite-difference algorithm.

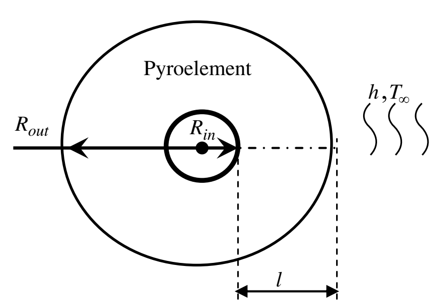

Fig. 1. Cylendrical electrocaloric element.