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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:

$$U = W_e + W_m + Q \tag{1}$$

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:

$$dW_e = EdD \quad (2)$$

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:

$$dD = \frac{\partial D}{\partial E}dE + \frac{\partial D}{\partial T}dT \quad (3)$$

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

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

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

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

The entropy S is given by

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

where

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

It is an exact differential then

$$\frac{\partial M}{\partial T} = \frac{\partial N}{\partial E} \quad (8)$$

From this we have:

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

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

$$\frac{\partial U}{\partial T} = c \gg E\frac{\partial D}{\partial T} \quad (10)$$

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

$$dQ = T\frac{\partial D}{\partial T}dE + cdT \quad (11)$$

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

$$D = D_r + \varepsilon E \quad (12)$$

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

$$P = P_r + \varepsilon E \quad (13)$$

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

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

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

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

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, $\frac{\partial T}{\partial r}|_{r=R_{in}} = 0\ K/m$, $-k\frac{\partial T}{\partial r}|_{r=R_{out}} = h(T-300)$
2) $T_{t=0} = 300$ K, $\frac{\partial T}{\partial r}|_{r=R_{in}} = 0\ K/m$, $T_{r=R_{out}} = 300$ 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 $\partial\varepsilon/\partial T = 1.8 \times 10^{-9}\ C/(m^3\ V\ K)$. 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.

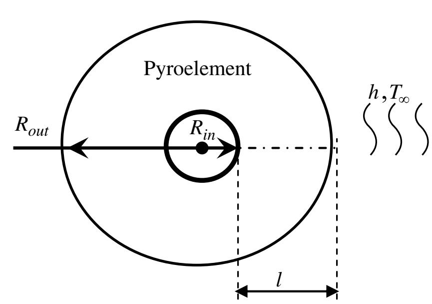

Fig. 1. Cylendrical electrocaloric element.

Table 1
Properties of the electrocaloric element.

Material	*ρ, Mass density* (g/cm^3)	*k, Thermal conductivity* (W/(m K))	*c, Heat capacitance* (J/(kg K))	*Dielectric constant ε/ε$_0$ at the room temp.*	*Dielectric constant ε/ε$_0$ at* T_c=140 °C
PMN-25PT	8000	0.25	312.5	2100	35,000

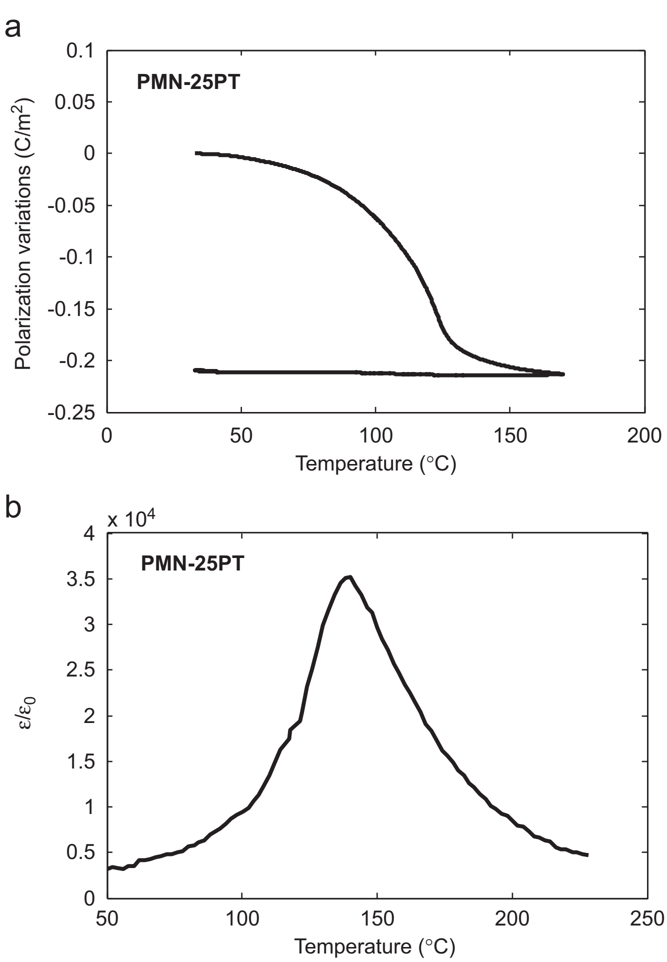

Fig. 2. Temperature dependence of the polarization and dielectric constant.

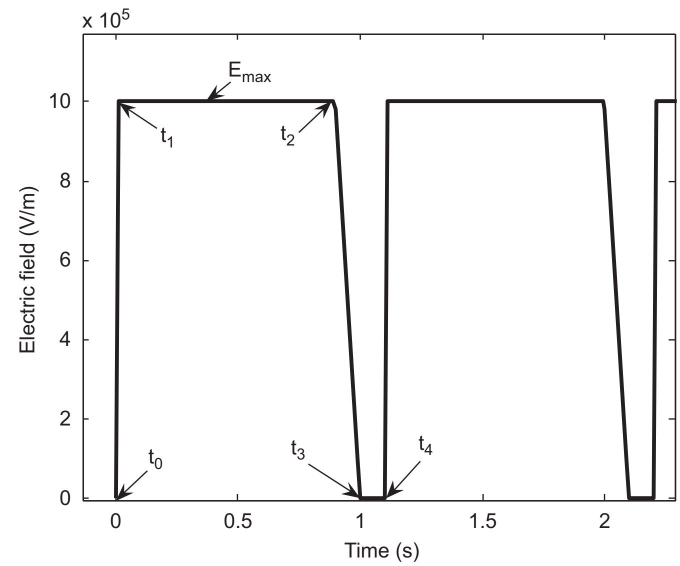

Fig. 3. Applied electric pulse to the electrocaloric element.

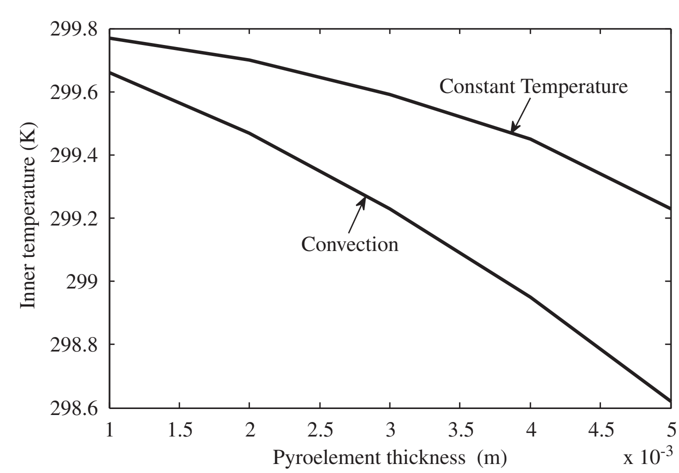

Fig. 4. Dependence of the inner temperature variations to the EC thickness.

Fig. 3 shows the applied electric field pulses on the electrocaloric element. Initially electric field grows relatively fast and swiftly switches from 0 up to E_{max} (maximum value of the electric field) in an adiabatic thermal process. The characteristic time of this switching process is about 10^{-12} s (interval t_0, t_1), which implies during this short period the electrocaloric element can not change its temperature immediately. This interval corresponds to charging of the capacitor and polarization of the ferroelectric. The electric field, which is now equal to $E_{max,}$ is then kept on the EC element during the interval of (t_1, t_2). Within this interval, the released heat during the charging of the capacitor spreads over the sample and the capacitor remains charged. After the moment t_2, the electric field is reduced to zero in an adiabatic thermal process (t_2, t_3). This interval corresponds to discharging of the capacitor, which leads to a decrease in temperature. The next pulse is applied to prevent the capacitor from turning back to its initial state. And, the cycle is then repeated.

The frequency and the amplitude of the applied periodical electric field pulses are 1 Hz and 1 kV/mm respectively. The periodical switching (the applied periodic sequence of pulses to the ferroelectric capacitor) results in a periodic cooling (heating) of the electrocaloric element and this leads to a redistribution of the temperature field along the sample (i.e. leads to release or absorption of the thermal energy in the ferroelectric material). After a series of cycles in which the electric field was applied to the sample, the temperature distribution between the insulated ($r=R_{in}$) and the heat exchanger ($r=R_{out}$) ends of the sample was determined.

Fig. 4 shows the dependence of the inner boundary temperature variations to the EC thickness. The temperature reduction increases with increase of EC thickness. In this figure the values of h and R_{in} are equal to 100 W/(m^{2}K) and 50 mm respectively.

Fig. 5 presents the numerical results corresponding to the radial temperature distribution of Fig. 1 in two cases of (a) outer boundary convection condition (b) outer boundary constant temperature condition. After a series of switching cycles, the temperature distribution attains a steady-state condition. The periodic temperature inhomogeneity due to these switching cycles generates a heat flux directed along the r axis of the sample. The heat flux is directed from the insulated end (inner side) to the surrounding (outer side), which leads to the heat removal or to a decrease in the temperature on the inner side. These temperature variations due to the applied periodical electric field to the dielectric material are the basis of electrocaloric effect. The maximum value of the temperature reduction at the insulated side of the sample is about 1.37° for outer convection condition and is about 0.76° for outer constant temperature condition. It is observed that inner boundary temperature reduction for outer boundary convection condition is more than one in constant outer boundary condition. In this figure the thickness of sample is equal to $l=5$ mm, $h=100$ W/(m^2 K) and the inner radius is chosen as $R_{in}=50$ mm. It is concluded that this transducer can be used as a heat pump, because it transfer heat from inner side to the outer side by alternative switching of the ferroelectric element.

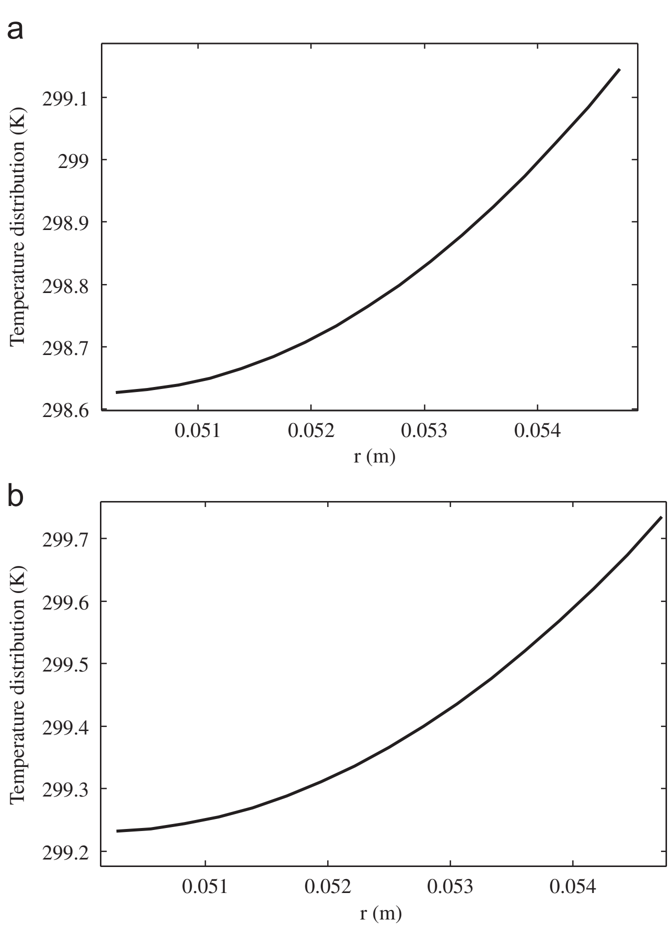

Fig. 5. Temperature distribution along the radial axis with the application of electric pulses of Fig. 3, (a) Outer boundary cconvection condition and (b) Outer boundary Constant temperature.

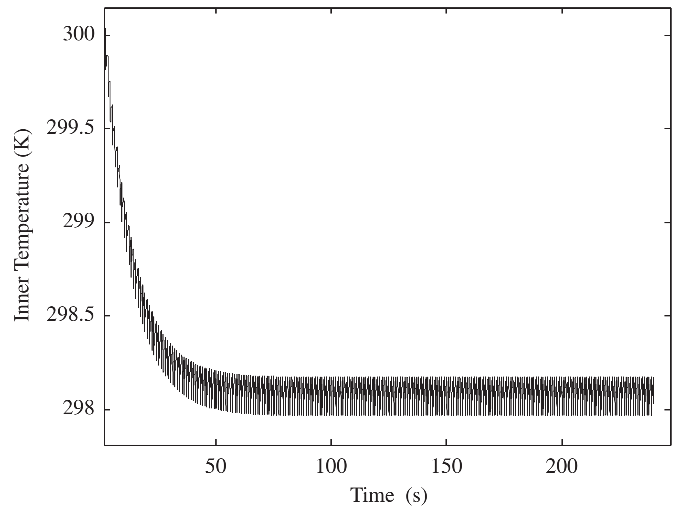

Fig. 6. Time variations of temperature at the inner side of the sample.

Fig. 6 shows the time variations of the inner boundary temperature. It is observed that after some switching cycles the temperature reaches a steady-state condition. It is necessary to note, that due to temperature dependence of permittivity and proper selection of working point, the exchanged heat during discharging process is more than one induced during charging. This distinctive feature is the main reason for cooling process on the inner side of the sample.

4. Conclusions

This work presented an analysis on the performance of an electrothermal ferroelectric transducer based on electrocaloric effect. It was shown that directed heat flux can be formed in an electrocaloric element. This can be done by periodically switching on the electrocaloric element that creates a temperature gradient which induces a heat flux. The PMN-25PT was chosen as electrocaloric element because of its high dielectric sensitivity. These results indicate that the power of the directed heat flux from one end of the sample to the other end strongly depends on the type of the boundary conditions. The temperature reduction in the case of convection condition is more than one at constant temperature. It is concluded that this transducer can be used as a heat pump, because it transfer heat from inner side to the outer side by alternative switching of the ferroelectric element.

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