Technical Note

Design and modeling of a fluid-based micro-scale electrocaloric refrigeration system

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A refrigeration system composed of silicon MEMS cooling elements is designed based on the electrocaloric (EC) effect in a P(VDF–TrFE–CFE) terpolymer, poly(vinylidene fluoride–trifluoroethylene–chlorofluoroethylene) 59.2/33.6/7.2 mol%. Each cooling element includes two diaphragm actuators fabricated in the plane of a silicon wafer, which drive a heat transfer fluid back and forth across terpolymer layers that are placed between them. In the EC effect, reversible temperature and entropy changes related to polarization changes appear in a material under the application and removal of an electric field. Finite element simulations are performed to explore the system performance. The effect of the applied electric field is studied, and the time lag between the electric field and the diaphragm motion is found to significantly affect the cooling power. A parametric study of the operating frequency, externally-applied temperature span, and the electric field amplitude are conducted. The results indicate that when the system is operated at a temperature span of 15 K, a cooling power density of 3 W/cm² and a percent of Carnot COP of 31% are achieved for one element.

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1. Introduction

Micro-scale coolers have a wide range of potential applications, such as cooling chip- and board-level electronics, sensors, and radio-frequency systems [1]. In recent years, new cooling technologies that take advantage of the thermoelectric [2–5], magnetocaloric [6] and electrocaloric (EC) [7] effects have attracted interest as traditional cooling methods cannot satisfy emerging requirements on energy efficiency and environmental impacts [8]. While thermoelectric coolers are gaining traction in applications, significant challenges exist to increase the figure of merit beyond unity due to the difficulty of reducing the thermal conductivity while maintaining good electrical properties [5]. The EC effect is a phenomenon in which reversible temperature and entropy changes appear in certain materials under the application and removal of an electric field. Applying the electric field orients the dipoles and reduces the entropy associated with the polarization. This process happens so fast (on the order of milliseconds [9]) that it can be considered to be adiabatic. The temperature of the material therefore increases, as required by the entropy decrease. Reversely, removing the electric field disorders the dipoles, increases the entropy, and cools the material. The main advantage of EC cooling over magnetocaloric cooling (which operates on an analogous principle) is that the high electric field required for the process is much easier and less expensive to generate than the high magnetic field required for magnetocaloric cooling [8].

Although the EC effect was first reported by Kobeco and Kurotschatov in 1930 [10], potential applications have been limited by the relatively low entropy and temperature changes for most ferroelectric materials (the highest value reported before 2006 was 2.6 K at an electric field of 3 V/μm and a temperature of 707 K for bulk Pb0.99Nb0.02(Zr0.75Sn0.20)Ti0.05O3 [11]). Recently, materials with a large EC effect have been discovered [12,13], suggesting practical applications in cooling devices. Among these materials, a P(VDF–TrFE–CFE) terpolymer, poly(vinylidene fluoride–trifluoroethylene–chlorofluoroethylene) 59.2/33.6/7.2 mol%, demonstrates an adiabatic temperature change of 16 K under an electric field of 150 V/μm over temperatures between 270 K and 320 K [14]. In this paper, we designed a refrigeration system based on the EC effect of this terpolymer.

In 2010, Ju proposed the design of a solid-state refrigeration system based on the EC effect where an EC material is dynamically
moved between a heat source and a heat sink [7]. Reducing the large thermal contact resistances at the interfaces between the EC material and the heat source/sink (which are periodically brought into and out of contact) is challenging in this design. Here, as shown in Fig. 1, a new EC effect-based micro-scale refrigeration system is designed that uses a heat transfer fluid to remove the contact resistance issue between the EC material and the heat sink/source. In the design, each cooling element includes two diaphragm actuators fabricated on a silicon wafer. A set of five terpolymer layers are placed between the two diaphragm chambers. Each element is designed such that the fluid flow direction is within the plane of the wafer.

The remainder of this paper is organized as follows. In Section 2, the design of the fluid-based EC micro-scale cooler is discussed in detail. In Section 3, finite element modeling is used to evaluate the full system performance with the multiphysics simulation software package COMSOL Multiphysics®.

2. Design concept

2.1. Overall design

The cooling element is 7 mm-long, 2.5 mm-wide, has a thickness of 250 μm, and includes two chambers made of cavities and diaphragms that are fabricated on a silicon wafer, as shown in Fig. 1. Five terpolymer layers of 10 μm thickness are located between the two diaphragm chambers. Each element is designed such that the fluid flow direction is within the plane of the wafer.

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2. Design concept

2.1. Overall design

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As illustrated schematically in Fig. 2, the EC-based thermodynamic refrigeration process in our cooler design includes four steps: (A) Heat absorption: the fluid absorbs heat from the cold side (heat source); (B) Polarization: the hot diaphragm moves up and the cold diaphragm moves down, the EC material is heated by applying the electric field and the fluid absorbs the heat from the EC material as it flows from the cold side to the hot side; (C) Heat rejection: the heat carried by the fluid is rejected to the hot side (heat sink) while the electric field is off; (D) Depolarization: the cold diaphragm moves up and the hot diaphragm moves down, then the fluid moves from the hot side to the cold side and releases heat to the EC material when the electric field is turned off. Through periodic cycling, heat is extracted from the cold fluid chamber and released to the hot chamber, and the fluid reaches its lowest temperature in the cold side.

2.2. Hot and cold chambers

The in-plane design offers efficient thermal isolation by enabling a 2 mm-long EC module between the two diaphragm actuators. The diaphragms are actuated electro-statically in the hot and cold chambers to drive the working fluid, which transfers heat between the two chambers. In this design, the bulk silicon substrate on which the device is grown is etched with “zipping” shaped
chambers under the diaphragms [15,16]. The silicon enables efficient heat transfer between the fluid and the heat source/sink to improve the performance of the cooling element. The “zipping” shaped substrate reduces the pull-in voltage required to actuate the diaphragms. Fins are built at the outlet of the chambers to guide the fluid and improve the heat transfer between the fluid and heat sink/source, as shown in Fig. 1.

2.3. Working fluid and thermal penetration

The relevant properties of the working fluid HT-70 are provided in Table 1. The height of the channels between the EC polymer layers and the space between the fins at the outlet of the chambers are determined according to the thermal penetration depth, $\delta$, which is defined by [15]

$$\delta = \sqrt{\frac{k}{\pi f \rho c}}$$

(1)

where $f$, $k$, $\rho$, and $c$ are the operating frequency and the fluid’s thermal conductivity, density, and specific heat. For HT-70, the thermal penetration depth at a temperature of 298 K is 25 $\mu$m at an operating frequency of 20 Hz, which is near the maximum practical operating frequency of the device. The channel height and fin space are therefore chosen to be 50 $\mu$m for the design. The properties of the terpolymer are also listed in Table 1. The thickness of the terpolymer layer is 10 $\mu$m, which is smaller than its thermal penetration depth of 34 $\mu$m at an operating frequency of 20 Hz and a temperature of 298 K.

3. System evaluation

3.1. Governing equations

The fluid flow is incompressible and described by the Navier–Stokes equations. The energy equation within the EC material is

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T - \dot{Q}.$$  

(2)

where $T$ is the temperature and $t$ is time. $\dot{Q}$ is the heat source term due to the EC effect of the material, which is described by

$$\dot{Q} = \rho T \left( \frac{\partial S}{\partial E} \right)_T \frac{\partial E}{\partial t}.$$  

(3)

where $S$ is the entropy and $E$ is the applied electric field [19]. The relationship between the entropy change and the electric field is obtained from experimental data [14]. For the P(VDF–TrFE–CFE) terpolymer, the entropy in Eq. (3) can be modeled as

$$S = C_1 E^2 + C_2 E,$$  

(4)

where $C_1 = -2.71 \times 10^{-15}$ J/m$^2$(kg K V$^2$) and $C_2 = -6.85 \times 10^{-8}$ J/m$^2$(kg K V). While the relationship between entropy and electric field is generally temperature-dependent, the EC effect of this terpolymer does not demonstrate a large deviation when the temperature changes from 270 K to 320 K [14]. Therefore, the entropy change is assumed to be temperature independent for simplicity within this temperature range.

We note that the reported dielectric loss of the terpolymer is small and is ignored in the modeling. At 150 V/\mu m, the input electric energy density calculated from the electric displacement – electric field hysteresis loop is 3 J/cm$^3$ [20], which is less than 7% of the material cooling energy density (43.2 J/cm$^3$).

3.2. Computational setup

The computational model is built based on the components shown in Fig. 1. The temperature at the hot end of the element is constant and is $T_H = 300.15$ K. The cold end also has a constant temperature range. The remaining surfaces are thermally insulated. The initial temperature for the whole system is a linear profile in the $x$-direction (see Fig. 1). The no-slip condition is applied to the solid–liquid interfaces. As the diaphragms are driven electro-statically, their actual motions are complicated and require detailed study. To simplify the model and the analysis, a sinusoidal motion with a 180$^\circ$ phase lag is applied for the cold and hot diaphragms. The displacement of the cold diaphragm is $z(x,y,t) = Z_{\text{max}}(x,y) \sin(2 \pi ft)$. The hot diaphragm and the cold diaphragm oscillate 180 out of phase but with the same amplitude. Here, $Z_{\text{max}}(x,y)$ is the amplitude of the diaphragm vibration. We assume that the fluid space in the chamber is a spherical cap. The cap base

![Fig. 2. The thermodynamic refrigeration cycle of a fluid element based on the EC effect. The process includes four steps: (A) heat absorption, (B) polarization, (C) heat rejection, and (D) depolarization.](image)

![Fig. 3. The smooth trapezoidal waveform of electric field applied to the EC module and the motion of the center point for the hot diaphragm. $\tau$ is the period of a cycle. $E_{\text{max}}$ is the amplitude of the electric field, $Z_{\text{max}}$ is the maximum amplitude of the hot diaphragm motion, $\Delta t_1$ is the transit time when the electric field rises/drops, $\Delta t_2$ is the time lag between the diaphragm motion and the electric field in the EC module.](image)

![Table 1. Properties of HT-70 and P(VDF–TrFE–CFE) terpolymer.](table)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\mu$ (Pa s)</th>
<th>$k$ (W/(m K))</th>
<th>$c$ (J/(kg K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT-70 [17]</td>
<td>1680</td>
<td>8.4 $\times$ 10$^{-4}$</td>
<td>0.065</td>
<td>970</td>
</tr>
<tr>
<td>P(VDF–TrFE–CFE) terpolymer [18]</td>
<td>1800</td>
<td>–</td>
<td>0.2</td>
<td>1500</td>
</tr>
</tbody>
</table>

$\dot{Q} = \rho T \left( \frac{\partial S}{\partial E} \right)_T \frac{\partial E}{\partial t},$
is a circle with a 2 mm diameter and the maximum height of the cap is 150 μm. So, $Z_{\text{max}}(x,y)$ represents the cap height at different positions. The hot and cold diaphragms prescribe the moving boundaries of the fluid flow. The arbitrary Lagrangian–Eulerian (ALE) moving-mesh method is used to handle the gas domain where there is a mesh deformation [21]. The maximum electric field applied to the material is limited by the breakdown of the film, which occurs at fields larger than 400 V/μm [22]. The maximum amplitude of the electric field here is 150 V/μm, which reduces the chance of the film’s breakdown due to the existence of defects. The detailed effect of the electric field on the system performance is discussed in the following section.

3.3. Results and discussions

In this section, the effects of the electric field applied to the EC module, the operating frequency, and the temperature span are investigated. For the electric field, a smooth trapezoidal waveform is used, as shown in Fig. 3. Two parameters are important: (i) $\Delta t_1$ is the transit time when the electric field rises from zero to $E_{\text{max}}$ or drops from $E_{\text{max}}$ to zero. (ii) $\Delta t_2$ is the time lag between the diaphragm motion and the electric field applied to the EC material. The cooling power density of the EC element is the space-averaged heat flux coming into the cold side from the cold end of the system. One example of the cooling power density as a function of time is shown in Fig. 4. Steady state is reached after 6 cycles when the operating frequency is 10 Hz, heat source temperature $T_C = 295.15$ K, $\Delta t_1 = 0.03$ s, and $\Delta t_2 = 0.025$ s. The temperature contours, pressure distribution and the fluid velocity at two different times in the tenth cycle are shown in Fig. 5. The results when the time is 0.94 s (9.4 $s\tau$, where $\tau$ is the period of the cycle), are shown in Fig. 5(a–c) and the results at $t = 0.988$ s (9.88 $s\tau$) are shown in Fig. 5(d–f). At $t = 0.94$ s, the hot diaphragm is moving up and the cold diaphragm is moving down. The electric field applied to the terpolymer is turning on, the temperature of the terpolymer is increasing, and heat is transferred to the fluid from the terpolymer. At $t = 0.988$ s, the diaphragm motion is reversed, and the electric field applied to the terpolymer is turning off. Thus, the temperature of the polymer drops, and the heat is transferred to the polymer from the fluid.

3.3.1. Effect of the applied electric field

We find that reducing the transit time $\Delta t_1$ increases the cooling power. At $T_C = 295.15$ K, when $\Delta t_1$ is reduced from 0.3 $s\tau$ to 0.1 $s\tau$ and

![Cooling power density](image_url)

**Fig. 4.** Cooling power density, which is space-averaged on the cold end surface of the element, vs. time. The operating frequency is 10 Hz, heat source temperature $T_C$ is 295.15 K, $\Delta t_1 = 0.03$ s, and $\Delta t_2 = 0.025$ s. The heat flux is negative, which indicates the heat flow direction is from the cold side to the hot side.

![Temperature](image_url)

**Fig. 5.** Distributions of temperature, pressure, and velocity in the $x$ direction in the element: (a) - (c) $t = 0.94$ s; (d) - (f) $t = 0.988$ s. At $t = 0.94$ s, the hot diaphragm is moving up, and the cold diaphragm is moving down. At $t = 0.988$ s, the diaphragm motions are reversed. The operating frequency is 10 Hz, heat source temperature $T_C$ is 295.15 K, $\Delta t_1 = 0.03$ s, and $\Delta t_2 = 0.025$ s.
is 0.25 s, the cooling power density increases from 0.143 W/cm$^2$ to 0.173 W/cm$^2$ at 1 Hz, and increases from 1.90 W/cm$^2$ to 2.13 W/cm$^2$ at 20 Hz. In Fig. 6, the effect of the time lag between the diaphragm motion and the electric field applied to the EC module is shown. When $\Delta t_2$ changes from 0.15 s to 0.35 s, a maximum value of the cooling power density is found to be 0.143 W/cm$^2$ at $\Delta t_2 = 0.25 s$ for a 1 Hz operating frequency. At 20 Hz, the maximum cooling power density is 1.89 W/cm$^2$ and still occurs at $\Delta t_2 = 0.25 s$. A 90° phase lag between the diaphragm motion and the electric field gives the best cooling power of the system. The reason is that at a 90° phase shift, when the flow direction starts to change, the electric field applied to the EC material is turning on/off at the same time. The temperature of the EC material changes simultaneously and thus the fluid transfers the heat with the EC material more effectively, achieving a larger cooling power.

3.3.2. Effect of the applied electric field

The effect of the operating frequency on the cooling power density is shown in Fig. 7. The transit time $\Delta t_1$ is 0.3 s, the time lag $\Delta t_2$ is 0.25 s, and $T_C$ is 295.15 K. From this figure, we can see that the cooling power density increases from 0.143 W/cm$^2$ to 2 W/cm$^2$ when the operating frequency increases from 1 Hz to 30 Hz. We note that at this point, the rate of increase with increasing frequency is reduced. In Section 2.3, it was described that based on the thermal penetration depth in HT-70, the channel height in the EC module is designed to be 50 µm at a frequency of 20 Hz. Thus, the cooling power density comes to saturation in the range of 20 Hz to 30 Hz.

The main input work from the diaphragm actuators is to overcome the fluid pressure drop in the system. The average pressure drop is 675, 1415, and 2260 Pa when the operating frequency is 10, 20, and 30 Hz. Below 30 Hz, the work loss caused by the pressure drop is small, thus the pressure drop does not affect the COP of the system much (less than 1%). However, when the pressure drop is higher, the voltage required to drive the diaphragms is larger. When the operating frequency is more than 20 Hz, the benefit of further increase to the cooling power is small and the penalty of the pressure drop is large. The COP of the system is defined by $COP = \frac{Q_C}{Q_H}$, where $Q_H$ and $Q_C$ are the heat fluxes at the hot and cold ends. The variation of COP with operating frequency is plotted in Fig. 8. The COP first increases and then drops when...
the operating frequency is increased from 1 Hz to 30 Hz. The best COP is 8.6 at 15 Hz, which is about 15% of the Carnot COP. The Carnot COP is $T_c/(T_H - T_c)$. When the frequency is higher than 15 Hz, the cooling power saturates, as shown in Fig. 7, which hurts the COP. We note that the thermal efficiency is our focus here and that the mechanical efficiency of the diaphragm is not included in our analysis.

3.3.3. Effect of the temperature span and the electric field amplitude

From the previous section, the maximum cooling power of the system comes to saturation at a frequency of 20–30 Hz and the maximum COP occurs at 15 Hz. In this section, the effect of the temperature span (i.e., the externally-imposed temperature difference between the heat sink and the heat source) is studied. We consider different electric field amplitudes when the heat sink temperature is fixed at 300.15 K and the operating frequency is 20 Hz, which is near the frequency where the maximum cooling power and COP occur. The results for the cooling power density, COP, and percent of Carnot COP are plotted in Fig. 9. As the temperature span increases for a given electric field amplitude, the cooling power and COP decrease, and the percent of Carnot COP has a peak value. As the electric field amplitude increases, the percent of Carnot COP increases and the maximum occurs at a larger temperature span. At an electric field amplitude of 50 V/μm, the adiabatic temperature change of the EC material is 2 K and the maximum temperature span that can be applied to the system is 5 K (i.e., beyond this value there is no cooling load). The cooling power and COP are very low due to the heat conduction loss in the x direction and the existence of thermal resistance in the silicon chamber, which is inherent for the in-plane design. With an increase of the electric field, the cooling power and COP increase. At 100 V/μm, the maximum percent of Carnot COP is 20% for a temperature span of 10 K. There is no cooling load when the temperature span exceeds 15 K. If the electric field is 150 V/μm, a 31% of Carnot COP and a cooling power density of 3 W/cm² are achieved for a temperature span of 15 K. There is no cooling load when the temperature span exceeds 30 K. Generally, the efficiency loss is mainly due to the thermal resistance from the heat source/sink to the chamber region, as shown in the temperature distribution in Fig. 5(a) and (d). For comparison, in a standard design of a thermoelectric cooler (i.e., the material thickness is larger than 1 mm), the cooling power density is 4 W/cm² and the best percent of Carnot COP is 15% when the ZT of the material is unity and the temperature difference is 15 K [23].

4. Conclusions

In this paper, a new micro-scale refrigeration system based on EC effect has been designed. Finite element simulations were used to evaluate the system’s thermal performance. The effect of the applied electric field was studied. The transit time over which the electric field changes has a small effect on system cooling power, while the time lag between the electric field and the diaphragm motion is found to play an important role. The maximum cooling power density tends to saturate above an operating frequency of 20 Hz and the best COP occurs at 15 Hz. The result indicates that a cooling power density of 3 W/cm² and a percent of Carnot COP of 31% are achieved when the system is operated at a temperature span of 15 K. Larger temperature difference between the heat sink and heat source or higher cooling power density could be achieved by increasing the magnitude of the electric field applied to the EC material.

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