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A novel thermomechanical energy conversion cycle

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HIGHLIGHTS

- Demonstration of a novel cycle converting thermal and mechanical energy directly into electrical energy.
- The new cycle is adaptable to changing thermal and mechanical conditions.
- The new cycle can generate electrical power at temperatures below those of other pyroelectric power cycles.
- The new cycle can generate larger electrical power than traditional mechanical cycles using piezoelectric materials.

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ABSTRACT

This paper presents a new power cycle for direct conversion of thermomechanical energy into electrical energy performed on pyroelectric materials. It consists sequentially of (i) an isothermal electric poling process performed under zero stress followed by (ii) a combined uniaxial compressive stress and heating process, (iii) an isothermal electric de-poling process under uniaxial stress, and finally (iv) the removal of compressive stress during a cooling process. The new cycle was demonstrated experimentally on [001]-poled PMN-28PT single crystals. The maximum power and energy densities obtained were 41 W/L and 41 J/L/cycle respectively for cold and hot source temperatures of 22 and 130 °C, electric field between 0.2 and 0.95 MV/m, and with uniaxial load of 35.56 MPa at frequency of 1 Hz. The performance and constraints on the operating conditions of the new cycle were compared with those of the Olsen cycle. The new cycle was able to generate power at temperatures below those of the Olsen cycle. In addition, the new power cycle can adapt to changing thermal and mechanical conditions.

1. Introduction

Harvesting thermal and/or mechanical energies that are typically wasted could contribute to more sustainable and efficient energy use. Waste mechanical energy is an unavoidable by-product of objects in motion and exists in the form of vibrations, shocks, or strains [1]. Sources of waste mechanical energy include fluid flow, household appliances, industrial equipment, motor vehicles, and structures such as buildings and bridges [1]. In addition, waste heat is the inevitable by-product of power, refrigeration, and heat pump cycles, according to the second law of thermodynamics [2]. In fact, many sources of waste heat, such as electricity generation and transportation systems, also waste mechanical energy.

The most widely used method to harvest mechanical energy is piezoelectric energy conversion [3]. It makes use of the piezoelectric effect to convert time-dependent mechanical deformations into electricity [1]. Other methods for direct mechanical to electrical energy conversion include electromagnet, electrostatic, and electroactive polymer generators [1]. Similarly, various methods are available to harvest waste heat. For example, Stirling engines [4] and organic Rankine cycles [5] have been used to convert low grade thermal energy into mechanical energy. Thermoelectric devices convert a steady-state temperature difference at the junction of two dissimilar metals or semiconductors into electrical energy [6]. By contrast, the Olsen cycle [7] performed on pyroelectric materials utilizes time-dependent temperature oscillations to convert thermal energy directly into electricity. Note that none of these energy conversion methods are capable of converting both thermal and mechanical energies directly into electricity.

Pyroelectric materials possess a temperature-dependent spontaneous polarization, defined as the average electric dipole moment per unit volume, in absence of an applied electric field [8]. A subclass of pyroelectric materials, known as ferroelectrics, has the ability to switch the direction and magnitude of the spontaneous polarization by reversing the applied electric field above the coercive electric field [9]. Pyroelectric materials are also piezoelectric, i.e., the electric charge at the material surface changes

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when the material is mechanically deformed. Applying a compressive stress in the poling direction decreases the electric displacement for a given temperature and electric field. The reduction in surface charge results in current in the external load.

This study aims to demonstrate the feasibility of a novel power cycle performed on pyroelectric materials to convert both thermal and mechanical energies directly into electrical energy. This new cycle was demonstrated on commercially available [001]-poled lead magnesium niobate-lead titanate $0.72PbMg_{1/3}Nb_{2/3}O_3-0.28PbTiO_3$ (PMN-28PT) single crystals.

2. Background

2.1. Dielectric hysteresis loops

Fig. 1a and b show the isothermal bipolar hysteresis curves in the electric displacement D vs electric field E diagram (D–E loops) exhibited by a typical pyroelectric material at two different temperatures T_{cold} and T_{hot} under compressive stress σ equal to 0 and σ_H. The D–E loops under any compressive stress traveled in a counter-clockwise direction. The electric displacement D of a pyroelectric material at temperature T under electric field E and compressive stress σ can be expressed as [9,10]

$$D(E,T,\sigma) = \varepsilon_0\varepsilon_r(T,\sigma)E + P_s(T,\sigma) \quad (1)$$

where ε_0 is the vacuum permittivity (=8.854×10^{-12} F/m) and $\varepsilon_r(T,\sigma)$ is the large-field relative permittivity of the material at temperature T and under stress σ. The saturation polarization $P_s(T,\sigma)$ corresponds to the electric displacement in the linear fit of D vs E at large field extrapolated to zero electric field [11] and the slope of this linear fit is the product $\varepsilon_0\varepsilon_r(T,\sigma)$. Other important properties include (i) the remnant polarization $P_r(T,\sigma)$ corresponding to the polarization under zero applied electric field, (ii) the coercive field $E_c(T,\sigma)$ corresponding to the electric field required to reach zero electric displacement, and (iii) the Curie temperature T_{Curie} defined as the temperature at which a ferroelectric material undergoes a phase transition from ferroelectric to paraelectric. This phase transition temperature is typically defined as the temperature corresponding to the maximum of the real part of the complex dielectric constant for given frequency and applied electric field [12].

2.2. Single crystal PMN-PT

Single crystal PMN-xPT has been widely used in mechanical sensors and actuators and their piezoelectric and dielectric properties have been studied extensively [11,13–25]. PMN-xPT possesses large piezoelectric constants near the morphotropic phase boundary (MPB) separating rhombohedral and tetragonal phases [20]. This phase boundary in PMN-xPT corresponds to x ranging between 27.5 and 33 mol% [19].

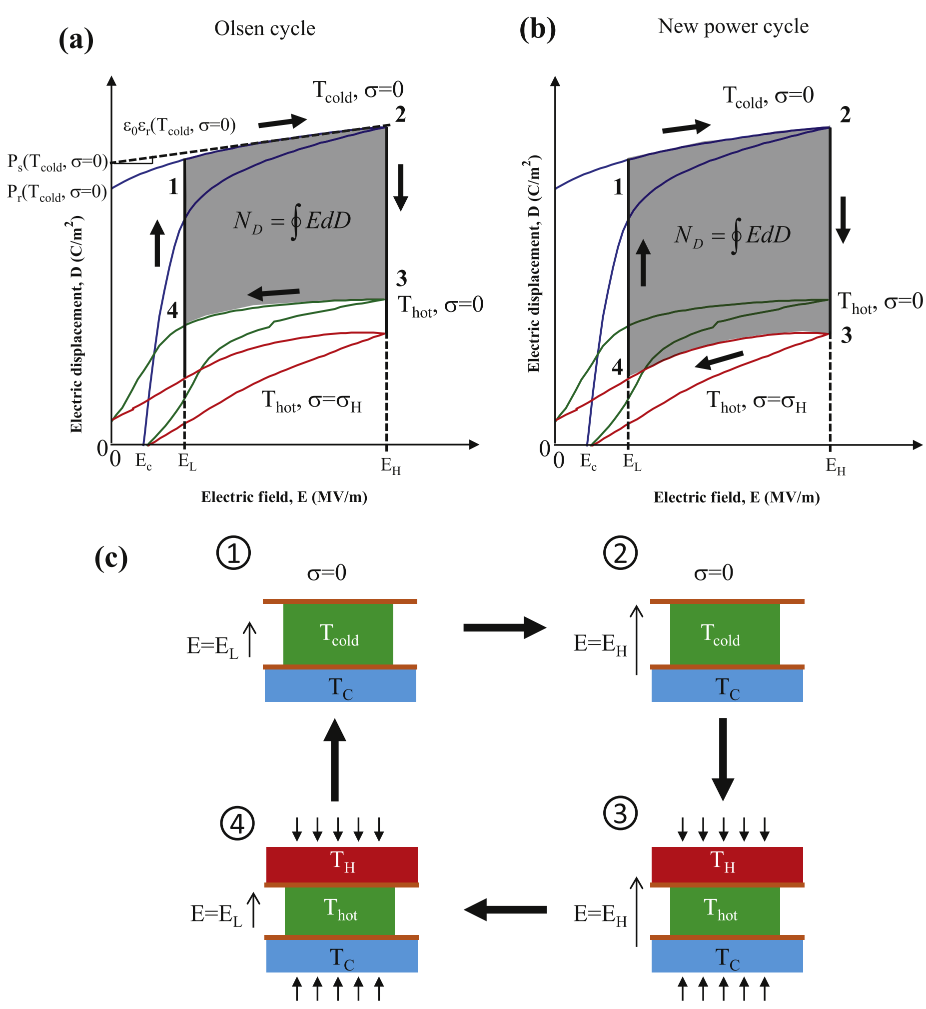

Fig. 1. Two-dimensional projections of (a) the Olsen cycle and of (b) the new power cycle in the D–E plane and electric displacement vs electric field loops at T_{cold} for uniaxial stress $\sigma = 0$ and T_{hot} for $\sigma = 0$ and σ_H. The electrical energy generated per cycle is represented by the grey areas enclosed by states 1–2–3–4. (c) The thermal, electrical, and stress states of the ferroelectric sample at each state of the new power cycle.