Waste Heat Energy Harvesting using PLZT Ceramics

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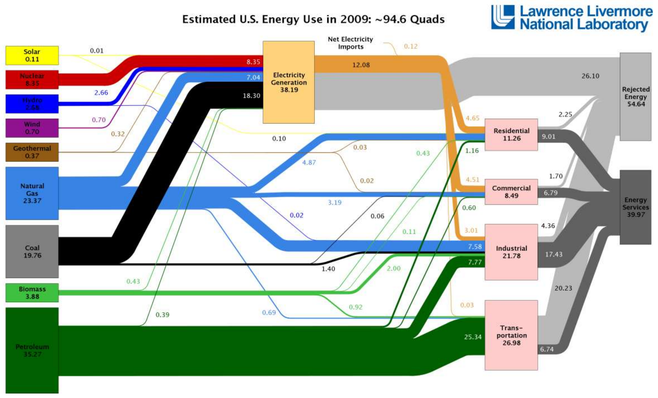
Abstract: Waste heat can be directly converted into electrical energy by performing the Olsen cycle on ferroelectric relaxor lanthanum doped lead zirconate titanate (PLZT). The Olsen cycle consists of two isothermal and two isoelectric field processes in the electric displacement versus electric field diagram. A maximum energy density of 888 J/L per cycle was generated with a 290 µm thick 8/65/35 PLZT ceramic for temperatures between 25 and 160˚C and electric fields cycled between 0.2 and 7.5 MV/m. A maximum power density of 55 W/L was obtained with a 250 µm thick 9.5/65/35 PLZT sample for operating temperatures between 3 and 140 ˚C and the electric field cycled between 0.2 and 6.0 MV/m. To the best of our knowledge, these are the largest pyroelectric energy and power densities experimentally measured with multiple cycles. The electrical breakdown strength and therefore the energy and power densities of the material increased as the sample thickness was reduced. Furthermore, the electrode material was found to have no significant effect on the energy and power densities for samples subject to the same operating conditions. However, samples with electrode material possessing thermal expansion coefficients similar to that of PLZT were capable of withstanding larger temperature swings. Finally, a physical model for estimating the energy harvested by ferroelectric relaxors was further validated against experimental data for a wide range of electric fields and temperatures.

Introduction

▪ Motivation

- In 2009, approximately 50% of the energy consumed in the United States was lost as waste heat typically discharged to the environment.[1]

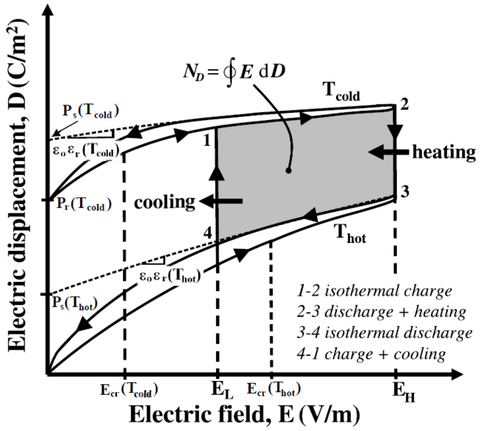


- The goal of this study was to perform a pyroelectric characterization of PLZT ceramics for their use in waste heat energy harvesting.

Olsen Cycle

▪ Principle

- When performed on pyroelectric material the Olsen cycle can convert thermal energy directly into electricity.[2]
- The cycle consists of two isothermal and two isoelectric field processes in the displacement versus electric field (D-E) diagram.[2]
- The generated energy density N_D is defined as the electrical energy produced per unit volume of the material per cycle.[2]



▪ Materials investigated

8/65/35 PLZT	9.5/65/35 PLZT
▪ Larger polarization spans ▪ Higher dielectric breakdown strengths ▪ High energy density N_D	▪ Faster relaxation ▪ Lower phase transition temperatures ▪ High power density P_D

▪ Modeling

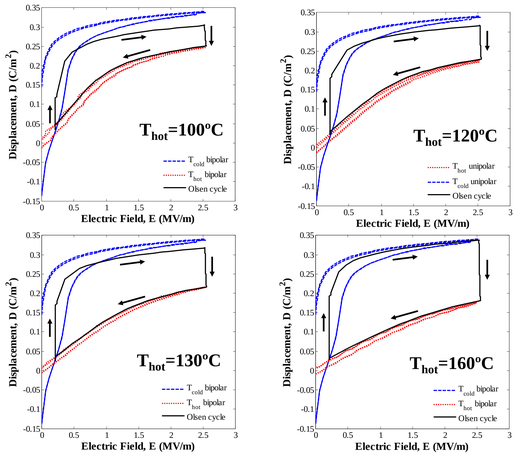
- A physical model for relaxor ferroelectric material undergoing the Olsen cycle was used to estimate N_D.[3]
- The model is valid for Olsen cycles performed under quasiequilibrium conditions.

$$N_D = (E_H - E_L)\left\{\frac{\varepsilon_0}{2}[\varepsilon_r(T_{cold}) - \varepsilon_r(T_{hot})](E_H + E_L) + \left[P_s(T_{cold}) - P_s(T_{hot}) + \frac{d_{33}x_3}{s_{33}}\right]\right\} \quad (1)$$

Notations:
N_D: energy density (J/m³)
E_H: high electric field (V/m)
T_{cold}: cold operating temperature (K)
T_{hot}: hot operating temperature (K)
E_L: low electric field (V/m)
ε_0: vacuum permittivity (F/m)
$\varepsilon_r(T)$: relative permittivity at T
$P_s(T)$: saturation polarization at T (C/m²)
d_{33}: piezoelectric coefficient (C/N)
s_{33}: elastic compliance (m²/N)
$x_3 = \alpha_3(T_{hot} - T_{cold})$
α_3: thermal expansion coefficient (1/K)

Experiments

- Sample thickness varied between 190 and 720 µm.
- Isothermal bipolar D-E loops were performed on 8/65/35 PLZT to evaluate properties $P_s(T)$ and $\varepsilon_r(T)$ between 45 and 160ºC for model predictions.
- Olsen cycles were performed varying T_{cold}, T_{hot}, E_H, E_L, and cycle frequency f.[4,5]

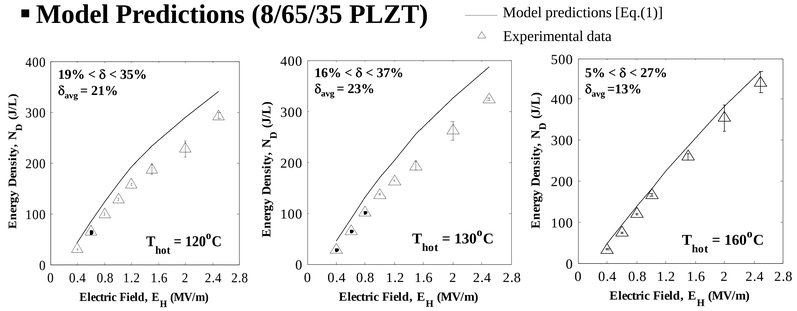


Isothermal bipolar D-E loops and experimental Olsen cycles for a 650µm thick 8/65/35 PLZT sample at E_L = 0.2 MV/m with T_{cold} = 45ºC and E_H = 2.5 MV/m for different values of T_{hot}.

- ➢ Olsen cycles bounded by D-E loops indicated no positive thermal expansion.
- ➢ For $T_{hot} \leq 130$ºC, process 1-2 of the Olsen cycle did not span D-E loops.
  - ➢ Possibly attributed to field-induced phase transition or mixed phases.

Results and Discussion

▪ Model Predictions (8/65/35 PLZT)

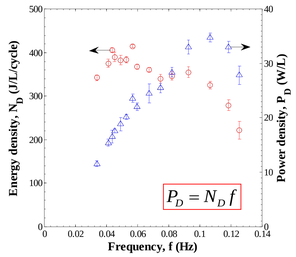


Experimentally measured energy densities generated by 8/65/35 PLZT under quasiequilibrium conditions versus high electric field E_H with T_{cold} = 45ºC and E_L = 0.2 MV/m for different values of T_{hot}.

- ➢ Average error between model predictions and experimental data was below 30%.
- ➢ Model did not account for presence of mixed ferroelectric phases.

▪ Effect of Frequency (9.5/65/35 PLZT)

E_L = 0.2MV/m, E_H = 5.0MV/m, T_{cold} = 23ºC, T_{hot} = 140˚C



Experimentally measured energy and power densities generated by 9.5/65/35 PLZT as a function of cycle frequency. The duration of isothermal processes 1-2 and 3-4 were ~1.5 s, while the duration of isoelectric processes 2-3 and 4-1 were the same and ranged from 1-10 s.

- ➢ Energy density N_D reached a maximum at 0.057 Hz.
- ➢ For frequencies below 0.057 Hz, N_D decreased due to excessive leakage current.
- ➢ As frequencies increased beyond 0.057 Hz, N_D decreased as Olsen cycles were not performed under quasiequilibrium conditions.

Conclusions

- The maximum energy density generated by 8/65/35 PLZT was **888 J/L/cycle** at 0.0178 Hz for T_{cold} = 25ºC, T_{hot} = 160ºC, E_L = 0.2 MV/m and E_H = 7.5 MV/m.
- The maximum power density obtained by 9.5/65/35 PLZT was **55 W/L** at 0.125 Hz for T_{cold} = 3ºC, T_{hot} = 140ºC, E_L = 0.2 MV/m and E_H = 6.0 MV/m.
- Model for estimating energy density generated by ferroelectric relaxors using the Olsen cycle was validated against experimental data.

➢ References

[1] Lawrence Livermore National Laboratory, "U.S. Energy Flow Trends – 2009".
[2] R. B. Olsen *et al*., Ferroelectrics, vol. 38, pp. 975-978, 1981.
[3] R. Kandilian *et al*., Smart Materials and Structures, vol. 20, no. 1, pp. 055020, 2011.
[4] F. Lee et al., Smart Materials and Structures, vol. 21, no. 2, pp. 025021, 2012.
[5] T. Chin et al., IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, under review