Linking Pyroelectric Energy Conversion Theory to Practice

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Pyroelectrics can convert heat into electricity by cycling around thermally- and electrically-induced polarization changes, where the energy density scales with the product of the polarization change and applied field [1,2]. To maximize the work per cycle and thus the efficiency, one would want to operate in the vicinity of a temperature-induced phase transition and under the largest applied field allowable. Following this logic, an extremely large energy conversion potential was measured in thin-film lead zirconate titanate (PZT) [1]. Thin films can also undergo fast thermal cycling, due to intrinsically low thermal mass, which enables high conversion power densities [2]. The challenges in realizing a pyroelectric energy conversion (PEC) system are multi-scale and multi-faceted, requiring the synthesis of phenomenological theory, classical thermodynamics, microfabrication, and system design. In this work, we will discuss our successes and challenges with relating modeled or measured material properties with experimental PEC and the lessons learned.

A classical thermodynamic analysis of PEC cycles provides guidance for selecting optimum operating temperatures and electric fields, where the material properties of interest can be extracted from adiabatic hysteresis loops and/or phenomenological modelling. The competing maxima of the pyroelectric coefficient, p, (representing energy out) and specific heat, Ce, (representing energy in) reveal a non-intuitive peak efficiency operating temperature relative to the zero electric-field phase transition temperature (Tc). At high stress fields, intrinsic to the thin film deposition process, and electric fields, where energy conversion is most attractive, p and Ce have been dramatically diminished and there is a second peak of efficiency dominated by the applied electric field at temperatures >1.2*Tc (Figure 1). Thermodynamic analysis suggests the Brayton or Carnot cycles are more power-dense than the standard Ericsson cycle due to high cycling rates enabled adiabatic heating processes (figure 2). In practice, the charging rate becomes a greater limiter of efficiency due to electrical losses in the system, not captured by the cycle analysis. The synchronization of the cycle when heating/charging a real microfabricated device is also found to be critical. We reveal important features of PEC, comparing modelled to measured performance, finding non-intuitive optimizations that will guide future development of PEC systems.

[1] A. Mischenko, Q. Zhang, J. Scott, R. Whatmore, N. Mathur, Science, 311 (2006) 1270-1271.
[2] S. P. Alpay, J. Mantese, S. Trolier-McKinstry, Q. Zhang, R.W. Whatmore, MRS Bulletin, 39 (2014) 1099-1111.
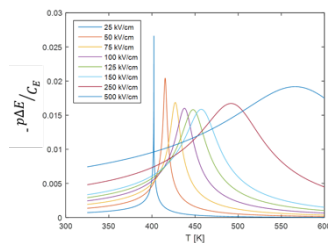
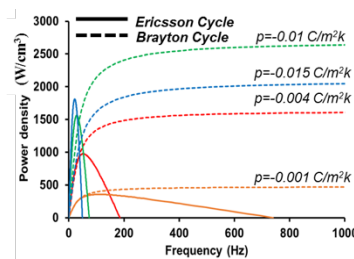**Figure 1**. Non-dimensional cycle efficiency metric versus

Figure 2. PEC cycle power density versus frequency over a range of pyroelectric coefficients for Ericsson and Brayton cycles