Additive Manufacturing of Energy Harvesting Material System for Active Wireless MEMS Sensors

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Agenda

- Motivation
- Background
- Technical Approach
- Results
- Conclusion
- Future Work

Motivation

- Highly efficient and environmentally benign power and fuel systems require:
  - Critical sensing in modern power plants and energy systems
  - Higher efficiencies in energy conversion
  - Lower emission for near-zero emission power plants

www.eia.gov/aeo/
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Motivation

• Monitoring/estimating operating conditions in real time is needed for high system performance and reliability
• Energy harvesting and direct sensing using piezoelectric ceramics

Turbines and Gasifiers:
• Up to 1200 °C
• Up to 1000 psi
• Oxidative, corrosive, highly reducing

Background

• Energy Harvesting

Energy Harvesting

Solar, Wind, Vibration, Thermal

Usable Energy

Electrical

Background

• Both piezoelectric and pyroelectric effects
• Harvest energy by coupling both effects in a single material

\[ S = \sigma^2 - T \alpha d \cdot E \]
\[ D = \varepsilon \sigma + \alpha E \]

\[ i = \frac{dP}{dt} = \frac{dQ}{dt} \]
\[ i = \frac{dP}{dE} = \frac{dQ}{dE} \]
Objective

- LiNbO$_3$/Graphene Ceramic Composites
- Modeling
- Binder Jetting Powder Bed 3D printing
- Thermal and Vibration Energy Harvesting

Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie Temperature ($^\circ$C)</th>
<th>Pyroelectric Coefficient ($\times 10^{-8}$ CK$^{-1}$ m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium Titanate, BaTiO$_3$</td>
<td>135</td>
<td>0.01</td>
</tr>
<tr>
<td>Lead Titanate, PbTiO$_3$</td>
<td>492</td>
<td>2.7</td>
</tr>
<tr>
<td>Lithium Niobate, LiNbO$_3$</td>
<td>1210</td>
<td>0.9</td>
</tr>
<tr>
<td>Lithium Tantalate, LiTaO$_3$</td>
<td>618</td>
<td>2.3</td>
</tr>
<tr>
<td>Lead Zirconate Titanate, PZT</td>
<td>365</td>
<td>4.7</td>
</tr>
<tr>
<td>Polyvinyl Chloride, PVC</td>
<td>100-266 (Melting Point)</td>
<td>0.01</td>
</tr>
<tr>
<td>Polyvinylidene Fluoride, PVDF</td>
<td>177 (Melting Point)</td>
<td>0.3</td>
</tr>
<tr>
<td>Zinc Oxide, ZnO</td>
<td>1975 (Melting point)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Energy Harvesting - Current Characterization

- Sample was cycled in a temperature range of 45$^\circ$C to 55$^\circ$C
- Current generated as a function of temperature change was recorded
Energy Harvesting

- A rectifying circuit was implemented to charge a commercial supercapacitor using the energy outputted by the sample.

Energy Harvesting at Elevated Temperatures

- Thermal loads at different temperature ranges were applied.
- Characterized pyroelectric coefficient of LiNbO$_3$ at these ranges.

\[ i = \frac{dQ}{dt} = \frac{dP}{dT} \]
**Energy Harvesting at Elevated Temperatures**

- Electrical resistors were introduced to calculate the power output at three different temperature ranges.
- Power decreases as temperature increases.

\[ P = I^2 R \Delta T \]

**Hybrid Energy Harvesting**

- Mechanical, thermal, and simultaneous loads were applied to the sample.

<table>
<thead>
<tr>
<th>Test</th>
<th>Loading (N)</th>
<th>Thermal Loading (°C)</th>
<th>Mechanical Loading (N)</th>
<th>Combined Loading (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mechanical</td>
<td>2500</td>
<td>Compression</td>
<td>Room Temperature</td>
<td>1000 Amplitude at 0.05 Hz</td>
</tr>
<tr>
<td>Pure Thermal</td>
<td>2500</td>
<td>Compression</td>
<td>Room Temperature</td>
<td>No Cycling Load</td>
</tr>
<tr>
<td>Mechanical at 50 °C</td>
<td>2500</td>
<td>Compression</td>
<td>50 °C</td>
<td>1000 Amplitude at 0.05 Hz</td>
</tr>
<tr>
<td>Mechanical at 60 °C</td>
<td>2500</td>
<td>Compression</td>
<td>60 °C</td>
<td>1000 Amplitude at 0.05 Hz</td>
</tr>
<tr>
<td>Combined</td>
<td>2500</td>
<td>Compression</td>
<td>Room Temperature</td>
<td>1000 Amplitude at 0.05 Hz</td>
</tr>
</tbody>
</table>

**Hybrid Energy Harvesting**

- A full bridge rectifying circuit was implemented to rectify the voltage output from the sample.

\[ D = dT \]
Hybrid Energy Harvesting

- Average voltage output across different resistors was measured under all testing conditions

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Peak Power (nW)</th>
<th>Load at Peak Power (MΩ)</th>
<th>Lowest Power (nW)</th>
<th>Load at Lowest Power (MΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mechanical</td>
<td>216</td>
<td>40</td>
<td>98.6</td>
<td>10</td>
</tr>
<tr>
<td>Pure Thermal</td>
<td>501</td>
<td>30</td>
<td>319</td>
<td>10</td>
</tr>
<tr>
<td>Mechanical at 50</td>
<td>320</td>
<td>50</td>
<td>108</td>
<td>30</td>
</tr>
<tr>
<td>Mechanical at 60</td>
<td>458</td>
<td>20</td>
<td>103</td>
<td>10</td>
</tr>
<tr>
<td>Combined</td>
<td>494</td>
<td>30</td>
<td>253</td>
<td>10</td>
</tr>
</tbody>
</table>

- Peak power at each loading condition was determined
- Maximum power observed under pure thermal conditions

3D Printing of Piezoelectric Ceramics
3D Printing of Piezoelectric Ceramics

- Have successfully been able to 3D print Barium Titanate using binder jetting technologies
- Print using Barium Titanate as the matrix for Lithium Niobate and PZT

Infiltration process
3D Printing of Piezoelectric Ceramics

- Poling process
- DC field of 1.2 kV/mm was applied
- 2 hours
- 120 ℃

3D Printing of Piezoelectric Composites

\[\varepsilon = k_0 - \frac{2(1 - 1)}{(1 + 2(1 - 3p))(1 + 2(3p))}\]

\[\varepsilon = k_0 - \frac{2(1 - 1)}{(1 + 2(1 - 3p))(1 + 2(3p))}\]

3D Printing of Piezoelectric Composites

- Applied thermal stresses to the different piezoelectric composites to obtain the displacements generated on the sample
3D Printing of Piezoelectric Composites

- Used generated displacement from previous calculation as input for piezoelectric simulations

Direct Sensing

- LN$_2$O$_3$ placed inside a tube furnace with controlled temperature
- Picoammeter used for current measurement
- DAQ and Labview used for data processing

Results – Direct Sensing

- Pyroelectric current output is proportional to $dT/dt$
Results – Direct Sensing

- Demonstrated temperature sensing capabilities of piezoelectric ceramics up to 500°C

\[ i = \frac{dQ}{dt} = Ap \frac{dT}{dt} = \frac{1}{\rho_k} \int p_{k1} s_{k1} \]

Conclusions

- Pyroelectric energy harvesting using a lead-free material was demonstrated
- Current and pyroelectric power were characterized at elevated temperatures
- Hybrid energy harvesting was also performed
- It’s possible to improve the amount of energy harvested by improving the harvesting circuit design and circuit elements
- Direct sensing under high temperature conditions was demonstrated
- Currently working on the development of piezoelectric ceramic composites using additive manufacturing technologies

Schedule

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1</td>
<td>Task 2</td>
<td>Task 3</td>
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<tr>
<td>Graphene Synthesis</td>
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<td>Task 4</td>
<td>Task 5</td>
<td>Task 6</td>
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<tr>
<td>Material Characterization</td>
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<td>Task 7</td>
<td>Task 8</td>
<td>Task 9</td>
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<tr>
<td>Hybrid Energy Harvesting</td>
<td>Hybrid Energy Harvesting</td>
<td>Hybrid Energy Harvesting</td>
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<tr>
<td>Improve Design</td>
<td>Improve Design</td>
<td>Improve Design</td>
</tr>
<tr>
<td>Final Report</td>
<td>Final Report</td>
<td>Final Report</td>
</tr>
</tbody>
</table>
Future Work

- Improve density of 3D printed ceramics
- Bimodal particle size distribution
- Surface modification
- Design of experiments for printing parameters
- Energy harvesting characterization of 3D printed ceramics

Acknowledgement

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- Program Manager: Barbara Carney, NETL

Student Involvement

Publications

Thank you

Questions?