Can A Cup of Hot Water and a Cup of Cold Water Cause a Fan to Work?

Place This Leg in Cold Water

Place This Leg in Hot Water

Will this fan spin?
Thermoelectric Materials Convert Heat to Electricity

Thermoelectric Device Schematic Figure of Merit for Properties of Materials

\[ ZT = \frac{\sigma S^2 T}{\kappa} \]

Efficiency Increases with Increasing ZT

Defining the Terms of the Figure of Merit

**Seebeck Coefficient (S)**
Describes how much energy the electrons that carry heat have

**Electrical Conductivity (\(\sigma\))**
Describes how easily electrons can move in the material

**Thermal Conductivity (\(\kappa\))**
Describes how easily the flux of heat can move in the material

Goal is to MAXIMIZE Electrical Conductivity (\(\sigma\)) and Thermopower (\(S\)) while MINIMIZING Thermal Conductivity (\(\kappa\))
Certain Materials Have Better Thermoelectric Properties Than Others

Copper | Bismuth Telluride | Zinc Oxide

Conductor | Semiconductor | Insulator

Predict Which One of These Materials Will Be The Best Thermoelectric

| Material | Material type | $|S|$ (µV K$^{-1}$) | $\sigma$ (S cm$^{-1}$) | $k$ (W m$^{-1}$ K$^{-1}$) | ZT (T = 298 K) |
|----------|---------------|------------------|------------------|------------------|----------------|
| ZnO      | Insulator     | 350              | $10^1$           | 50               | $\approx 10^{-3}$ |
| Bi$_2$Te$_3$ | Semiconductor | 200              | $10^4$           | 1                | $\approx 1$       |
| Cu       | Metal         | 7.6              | $10^7$           | 400              | $\approx 10^{-3}$ |
Thermoelectric Devices are Used In Applications Today

Multiple Devices Make a Module

Heat absorbed

Substrates
Thermoelectric elements
Metal interconnects
External electrical connection

Heat rejected

Heat absorption
Heat rejection

Thermoelectric devices

Modules Can Be Used in Automobiles

Cooled by engine coolant system
Thermoelectric Modules


Concept Images by: BMW, Ford, and BSST
A Lot of Energy is Converted to Waste Heat Currently

Recovery of 16% of the Rejected Energy Would Cover the Commercial Sector
Flexible Thermoelectrics Could Be Implemented Everywhere

In The Laboratory…

And Even on Mars

On Your Wrist…
Polymer Materials Can Be Made to Be Flexible or Rigid
Properties of the Polymer are Determined at the Nanoscale

Polymer Length Matters
Monomer → Polymer 1 → Polymer 2

Polymer Chemistry Matters
Monomer → Polymer 1 → Polymer 3

Polymers, Like Standard Materials, Can Have All Types of Behavior

Insulator

Semiconductor

Conductor
Plastic Thermoelectric Materials Exist and Work Well


<table>
<thead>
<tr>
<th>System</th>
<th>(\sigma) (S cm(^{-1}))</th>
<th>S ((\mu)V K(^{-1}))</th>
<th>(S^2\sigma_{\text{max}}) ((\mu)W m(^{-1}) K(^{-2}))</th>
<th>(\kappa) (W m(^{-1}) K(^{-1}))</th>
<th>(ZT_{\text{max}})</th>
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</thead>
<tbody>
<tr>
<td>PEDOT:PSS</td>
<td>1.32</td>
<td>18.9</td>
<td>0.05</td>
<td>0.24-0.29</td>
<td>6 x 10(^{-5})</td>
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<tr>
<td>Te Nanowires</td>
<td>0.1</td>
<td>40.8</td>
<td>27</td>
<td>2</td>
<td>4 x 10(^{-4})</td>
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<tr>
<td>PEDOT:PSS + Te</td>
<td>19.3</td>
<td>163</td>
<td>70.9</td>
<td>0.22-0.30</td>
<td>0.10</td>
</tr>
</tbody>
</table>
All Plastic Materials Have $ZT = 0.42$, Approaching Standard Modules

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