Thermoelectric Wood Stoves

Thursday, September 21, 2017
10:00 AM ET

In support of the Alliance for Green Heat’s 4th Wood Stove Competition in November 2018
Quick Notes

- Two Audio Options: Streaming Audio and Dial-In.
  1. Streaming Audio/Computer Speakers (Default)
  2. Dial-In: Use the Audio Panel (right side of screen) to see dial-in instructions.
- Call-in separately from your telephone.
- Ask questions using the Questions Panel on the right side of your screen.
- The recording of the webinar and the slides will be available after the event. Registrants will be notified by email.
✓ 501c3 nonprofit
✓ Promotes clean & efficient biomass heaters
✓ National voice for wood heat consumers
✓ Hosts design competitions
✓ Encourages transparency from manufacturers and regulators
• 4th Wood Stove Design Challenge
  • November 9-14, 2018
  • National Mall in Washington DC
• Two Competition Categories:
  • Automated stoves
  • Thermoelectric stoves
Thank you!

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(for thermoelectric issues)

Alliance for Green Heat
Takoma Park, MD
www.forgreenheat.org
301-204-9562
The national trade association for the modern wood heating industry.

- Engage in technical codes and standards development, public advocacy, and education.

- 100+ members and associates across the US and Canada:
  - Fuel Producers
  - Manufacturers
  - Sellers
  - Installers
  - Service Providers
  - Universities
  - Non-profits & NGOs
  - Government agencies
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Communication Operations, Membership
• What is a Thermoelectric?

• What can you do with it?

• How do you do it?
What is a Thermoelectric?

Materials that directly turn heat into electricity with no moving parts
IN THE WESTINGHOUSE Research Laboratories at Pittsburgh I saw an old-fashioned copper teakettle bubbling away over a gas burner while waltz music came from a radio beside it. A homely scene, but deceptive, for unless hundreds of scientists and engineers throughout the world turn out to be wrong, it was a symbol of future power as exciting in its implications as another kettle which stirred the imagination of a boy named James Watt two centuries ago. A cable running from the kettle to the radio furnished its electric power — power produced by the same flame that boiled the water. In the base of the kettle was a small pioneer “thermoelectric generator” which converts heat directly into electric current, with no intermediate machinery.

Watt’s teakettle grew up to be a steam boiler, and most of today’s electric power is produced by burning fuel under boiler pressure. But the thermoelectric generator is the ancestor of more useful devices than anyone dreamed of in Watt’s time: telephones, electric lights, electric motors, and much more.

Today’s Alchemist is Opening a New World
The Alphabet Energy E1™
Heat Recovery for MW Diesel & Nat Gas Engines in Remote Service

15 kW demonstrated output in the field – most powerful thermoelectric generator ever built
The Alphabet Energy E1™ Thermoelectric Generator
The Alphabet Energy E1™ in the Eagle Ford, Texas
E1 Gen III – 25kW in development
The Power Generating Combustor - PGC

- 2.5kW Net Power (5kW Gross)
- Quad-O combustion efficiency
- Power for instruments, communications, cathodic protection, etc
- Powers air compressor to eliminate gas hydraulics
- Permitted as a generator not a flare.
350W Peak power on a 5.3L truck
155W Average City & Highway.

The PowerModule fits in the exhaust system, extracting heat and generating power which unloads the alternator and improves fuel economy.

Transferring exhaust heat to the engine coolant accelerates warm-up and further boosts efficiency.

3% fuel economy improvement,
A key technology in satisfying 2025 CAFE standards
Scalable Automotive Architecture

- Units for smaller engines
- Exhaust Gas Recirculation Cooler on Diesel Engines
1. Thermoelectric Material Selection
2. Thermal Interfaces
3. Thermal Resistance Matching
4. Power Conditioning
### Material Selection

<table>
<thead>
<tr>
<th><strong>Material</strong></th>
<th><strong>Key Features</strong></th>
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| **Lead Telluride**         | • High Temperature operation  
• High efficiency  
• Expensive Raw Materials - commercial dead-end for large volume applications.  
• Require Vacuum.  
• Not commercially available |
| **Half Heusler**           |                                                                                  |
| **Skutterudite**           |                                                                                  |
| **LAST**                   |                                                                                  |
| **Tetrahedrite / MgSi**     | • AE Material  
• Medium-high temperature operation  
• High efficiency  
• Abundant raw materials - Low cost at scale.  
• Operates in air  
• Production all committed. |
| **Bismuth Telluride**      | • Low-Medium temperature operation  
• Lower power than others  
• Operates in air  
• Commercially available  
• Your only real option. |

**Marlow** - highest power, reliability & cost.  
Alternatives: **Tellurex, Ferrotec, Thermonamics**

Performance may vary – datasheets rarely accurate

250C max operating condition, some suppliers quote 300C but this is usually due to poor thermal contact and won’t yield benefits.
Putting it together

- Getting good thermal contact between heat exchanger and TE device while minimizing thermal stress is essential

- Thermal Interface Materials
  - Graphite – up to ~400C, not dielectric, a lot of pressure
  - Thermal Grease – 200C ish, dry out & pump out
  - Silicone Gap Pad – 200C ish, bubbles

- Careful of thermal bypass losses
Thermal Resistance Matching

Efficiency a Device Temperature Gradient

This means half your temperature drop is across the TE (unless limited by operating temp)
• Power Output is DC
• Requires Max Power Point Tracking
• Voltage & Current will vary with temperature and flow
• May not be the voltage you want.

- For DC-AC Power Solar Inverters work with Thermoelectrics
  - Be careful of dielectric strength

- For DC-DC Linear Technologies make a demo-board
Available to consult:

adam@lorimer-intl.com

925 408 1812
Design and Engineering of Thermoelectric Devices

G. Jeffrey Snyder, Northwestern University

http://thermoelectrics.matsci.northwestern.edu
Thermoelectric Device

Thermoelectrics
Convert Heat into Electricity

Heat Flow drives free electrons and holes from hot to cold

Voltage Produced
Seebeck effect
or Thermoelectric Power

\[ V = S \Xi T \]

Seebeck Coefficient \( \alpha \)
Efficiency \( \sim zT \)

\[ zT = \frac{S^2}{\rho K} \]

Typically \( zT < 1 \)

Thermoelectric Applications

Solid State Advantage
- No moving parts
- No maintenance
- Long life
- Scalability

Cooling - Thermal Management
- Small Refrigerators
- Optoelectronics
- Electric Vehicles
  - Zonal HVAC

Power Generation (heat to electricity)
- Spacecrafts
  - Voyager over 40 years!
- Remote power sources

Energy Harvesting
- Remote Sensor Power

Gentherm Zonal HVAC

2012 Mars Rover Curiosity

CASSINI SPACECRAFT

Thermoelectrics
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Co-Generation

Combined Heat and Power
  Burn Fuel to produce Heat
  Convert Heat to Electricity
  Utilize waste Heat for heating

Common for institutional power plans
  Universities
  Factories
  Where efficiency is valuable
  • 10% of Europe electricity is cogen

Could be used anywhere high exergy content fuel is used for heating
  ~90% efficiency in Electricity Generation
  Capital, Maintenance cost is primary issue
Thermoelectric Energy Harvesting

Situations where replacing a Battery is insufficient
- Li-ion ~ 1kJ/cm³
- 10% charge loss/month ~ 40µW/cm³
- one day recharge ~ 10 mW/cm³

Examples
- Remote Sensors, communications
  - Low average power consumption
- Wearable electronics

Ambient Energy source available
- Light (PhotoVoltaic)
- Vibration
- Heat (ThermoElectric)
Thermoelectric Stove

Waste heat – Cogeneration example
Thermoelectric powered fan improves combustion
• 95% less smoke (CO), pollution
• 50% less fuel
• recharges cell phone, LED lights.

http://biolitestove.com
Conceptual Design of Thermoelectric Generators
Energy Laws

1st law of thermodynamics
Energy is Conserved

2nd law of thermodynamics
Entropy ≥ 0

Example 1: Heat Conduction
\[ Q_h = Q_c \] (1st law)
\[ T_h > T_c \] (2nd law)

*Heat flows from Hot to Cold*
(Unless there is work being done to system)

Example 2: Heat Engine
\[ Q_h = Q_c + W \] (1st law)

Efficiency \[ \eta = \frac{W}{Q_h} \]

\[ \eta \leq \frac{\Delta T}{T_h} \] (Carnot Efficiency)

*Efficiency always less than Carnot*
Device Figure of Merit $ZT$

Efficiency of Thermal to Electric Energy Conversion

TE Module Electrical Output

Open Circuit Voltage

\[ V_{OC} = S \Delta T \]

Constant Temperature I-V curve

Slope = Resistance

\[ V = IR \]

Power (mW)

Current (mA)

0.86 W heat

1.17 W heat

Voltage

0 2 4 6 8 10 12

0 2 4 6 8 10 12 14

Power (mW)

Ukraine 1

205°C

1.17 W

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Effective Thermal Model

Thermal model

Thermal Circuit

\[ \Delta T_{\text{supply}} \]

\[ \Theta_{Hx,hot} \]

\[ T_h \]

\[ \Theta_{TE} \]

\[ \Delta T_{TE} \]

\[ T_c \]

\[ \Theta_{Hx,cold} \]

Maximizing Power

Thermal Impedance Match

maximum power when

$$\Theta_{TE} = \Theta_{Hx}$$

so Heat exchangers determine heat flux

$$Q = \frac{\Theta_{supply}}{\Theta_{Hx} + \Theta_{TE}}$$

Efficiency determines power

$$P = \eta Q$$

ZT determines efficiency

$$P_{\text{max}} = \frac{\Delta T^2}{4T_h\Theta_{Hx}} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c/T_h}$$

Device Efficiency from \( ZT \)

Device Figure of Merit \( ZT \)

\[
\eta = \frac{\varpi T}{T_h} \frac{\sqrt{1 + zT} - 1}{\sqrt{1 + zT} + T_c / T_h}
\]

\( \varpi \) is the Carnot Factor, \( \eta \) Reduced Efficiency

Seebeck Coefficient \( S \)

Electrical Resistance \( R \)

Thermal Conductance \( K \)

\[
ZT \approx \frac{S^2}{RK} \frac{T_c + T_h}{2}
\]

Device \( ZT \) is approx. an average of Materials figure of merit \( zT \) over the temperature range of use

ZT or Cost?

Lowest system cost/W is usually dominated by heat exchanger cost rather than TE material cost

- even $200/kg (Bi$_2$Te$_3$) is OK

Power increases with ZT so cost directly depends on ZT but not TE cost

\[
\frac{Cost}{W} \approx \frac{\text{Cost\%}}{\text{Area} \cdot 4 \cdot ZT}
\]

ZT is TE cost metric

Chris Dames, Scripta Materialia 111 16–22 (2016)
Thermoelectric Conceptual Design
Wood Stove

http://www.caframolifestylesolutions.com/ecofan/
Power Estimate

Thermal model

Heat transfer Coefficient

Cross sectional Area $A$

$$h_{Hx} = \frac{1}{\Theta_{Hx} A_{Hx}}$$

forced air forced water

$$h_{Hx} \approx 0.004 \text{ W/cm}^2\text{K} \quad h_{Hx} \approx 0.6 \text{ W/cm}^2\text{K}$$

$$\frac{P_{max}}{A_{Hx}} = \frac{\Delta T_{supply}^2 h_{Hx} \eta_{r,d}}{4T_h}$$

thermal impedance match sets target size of TE modules

$$\eta_r \approx 0.15$$

for Bi$_2$Te$_3$ modules

TE Modules and Use

http://hi-z.com/products/

Figure 1: HZ-14 High Voltage

Figure 2: Heat source and sink

Figure 5: Module insulation

Power and Efficiency Curve

- Pwr
- Eff

Power (watts) vs. Current (amps)
Module Failure Example

Reason for failure: Solder reacted with PbTe at elevated temperatures – crack formation at interface.

Crack at Metal – TE Interface

Stress Model: stress concentration at hot junction

ITRI Taiwan
Wood Stove Challenges

Performance goal
3W commercialized (Ecofan)
10-20W demonstrated (Hi-Z)
>50 W will be a challenge
>500 W may require ARPA-E level
investment

Modules
Commercial Bi₂Te₃-based
• < 250°C special modules (Hi-Z)
• < 120°C for Peltier cooler
High, Mid temp modules
• PbTe, H.Heusler, Skutterudite, Silicide, etc.
• evolving. Blog may be helpful

Technical Challenges
Hot side Heat Exchanger
• Thermal Interface to TE module
  – ~200psi pressure and TIM?
  – Thermal Interface Resistance
• Fouling and Corrosion
Cold Side Heat Exchanger
• Passive (no power) or Active (fan)?
• Interface to TE module
  – Thermal Interface Resistance
  – ~200psi pressure and TIM grease
Thermal management
• Keep TE at right temperature
  – too small ΔT: no power
  – To high T_{hot}: degrades
Power Management
• Impedance match (transformer)
• Energy storage?
Summary

Design issues
- Thermodynamics
- Heat Exchanger
- Impedance Matching
- Electrical Output
- Mechanical Issues
- Fabrication
- Cost

\[ Q_h \]
\[ W \]
\[ Q_c \]
Acknowledgements

http://thermoelectrics.matsci.northwestern.edu