Solid-State Energy Conversion Overview

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Overview

• Potential of Thermoelectric Applications in Vehicles

• Thermoelectric Materials

• Vehicular Thermoelectric Generators

• Vehicular Thermoelectric Air Conditioner/Heater

• Summary
Vehicular Thermoelectric Generators (TEG’s)

• Generate Electricity Without Introducing any Additional Carbon into the Atmosphere
Vehicular Thermoelectric Air Conditioner/Heater (TE HVAC)

- Maintain Vehicle Occupant Comfort With Major Reduction of Fuel Use

- Eliminate Vehicular Use of R134a Refrigerant Gas which has 1300 times Greenhouse Gas Effect as CO$_2$, the Primary Greenhouse Gas of Concern
First Application of Thermoelectric Generator in Vehicle

Front View

Rear View
Beltless or More Electric Engine

Modular HVAC
Variable speed compressor more efficient and serviceable
3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat

Shore Power and Inverter
Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power

Down Converter
Supplies 12 V Battery from DC Bus

Compressed Air Module
Supplies compressed air for brakes and ride control

Electric Water Pump
Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

Auxiliary Power Unit
Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight

Starter Generator Motor
Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

Electric Oil Pump
Variable speed Higher efficiency
Current TE Materials

P-type TE material

N-type TE material

Ref: http://www.its.caltech.edu/~jsnyder/thermoelectrics/
TE Materials Performance: Figure of Merit (ZT)

Electrical conductivity

Seebeck coefficient or thermopower $(\Delta V/\Delta T)$

\[ ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \cdot T \]

Total thermal conductivity

$\sigma \alpha^2 =$ Power Factor

$\sigma = 1/\rho =$ electrical conductivity

$\rho =$ electrical resistivity

Unusual Combination of Properties
Nanoscale Effects for Thermoelectrics (courtesy Millie Dresselhaus, MIT)

Interfaces that Scatter Phonons but not Electrons

- **Electrons**
  - Mean Free Path: $\Lambda = 10-100$ nm
  - Wavelength: $\lambda = 10-50$ nm

- **Phonons**
  - Mean Free Path: $\Lambda = 10-100$ nm
  - Wavelength: $\lambda = 1$ nm

[Diagram showing electron and phonon interfaces with scattering and non-scattering properties]
Atomic Structure of Skutterudites

Cobalt atoms form a \textit{fcc} cubic lattice
Antimony atoms are arranged as a square planar rings
There are 8 spaces for the Sb\textsubscript{4} units
6 are filled and 2 are empty

\[ \text{CoSb}_3 [\text{Co}_8(\text{Sb}_4)_6] \]

Atoms can be inserted into empty sites. Atoms can “rattle” in these sites – scatter phonons and lower the lattice thermal conductivity.
Highest ZT Achieved with Triple-filled Skutterudites

\[ ZT_{\text{ave}} = 1.2 \]

2. X. Shi, et al., submitted (2009)

- \( \text{Ba}_{0.08}\text{La}_{0.05}\text{Yb}_{0.04}\text{Co}_{4}\text{Sb}_{12.05} \)
- \( \text{Ba}_{0.10}\text{La}_{0.05}\text{Yb}_{0.07}\text{Co}_{4}\text{Sb}_{12.16} \)

Materials:
- \( \text{Bi}_2\text{Te}_3 \)
- \( \text{PbTe} \)
- \( \text{SiGe} \)
- \( \text{Ba}_0.24\text{Co}_{4}\text{Sb}_{12} \)
- \( \text{Yb}_0.12\text{Co}_{4}\text{Sb}_{12} \)
University/industry collaboration, $9M/yr over 3 years
LOIs were due May 21, 2010
Proposals due June 22, 2010

Key Element 1: Materials.
Key Element 2: Thermal management.
Key Element 3: Durability.
Key Element 4: Interfaces
Key Element 5: Heat sink design.
Key Element 6: Metrology.
Typical Waste Heat from Gasoline Engine Mid Size Sedan

- **Combustion**
  - 100% Gasoline

- **Engine**
  - 30%

- **Exhaust Gas**
  - 40%

- **Coolant**
  - 30%

- **Friction & Radiated**
  - 5%

- **Mobility & Accessories**
  - 25%

Vehicle Operation
BMW 530iA at 130 km/h, Exhaust gas back pressure limited to 30mbar at 130km/h

Slide courtesy of BMW
TEG’s are Ideally Compatible with Regenerative Braking

Slide courtesy of BSST
Demonstration TEGs In Ford Fusion, BMW X6 and Chevy Suburban
Thermoelectric Power Generation – The Next Step for CO₂ Reductions

Average demand for electric power
Fraction of electricity on total FC.

- 190 W 2% NEDC customer
- 330 W 3.5% NEDC customer
- 390 W 4% NEDC customer
- 750 W 6% NEDC customer
- 1000 W 8% NEDC customer

Source: BMW Group
BMW integrating a TEG with the EGR cooler of a Diesel engine.

The infrastructure for a TEG (water cooling, by-pass, exhaust-flap) is available in today’s EGR coolers.
BMW Diesel Engine EGR TEG.

Source: BMW Group
BMW EGR-TEG.

EGR cooler section

Thermoelectric generator

Output: approx. 250W

Source: BMW Group
TE HVAC Approach

- Develop test protocols and metrics for real-world automotive TE HVAC system usage

- Use CAE, thermal comfort models, and subject testing to optimize heating/cooling node locations

- Develop high-efficiency advanced thermoelectric materials and assemblies

- Design, integrate, and validate performance of a production prototype TE HVAC in a demonstration vehicle
Zonal Thermoelectric Air Conditioner/Heater (HVAC) Concept

Zonal TE devices located in the dashboard, headliner, A&B pillars and seats / seatbacks
Thermoelectric HVAC Advantages for PHEV, HEV, EV or FC Vehicles

- Occupant Heating During Battery Propulsion (No Engine Heat)
  - Resistance Heating Inefficient

Occupant Cooling
- Electric Compressor Refrigerant Gases
  > Need R134-a Replacement

Thermoelectric HVAC Zonal Concept
  > Cooling COP 1.5
    Augment or Replace Compressed Gas Unit
  > Heating COP 2.5
    Replace Resistive Heaters
    Typical COP 1.0
Battery Temperature Impacts PHEV, HEV and EV Performance and Service Life

Temperature affects battery operation

> Round trip efficiency and charge acceptance
> Power and energy
> Safety and reliability
> Life and life cycle cost

Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost
Vehicular Thermoelectric Hybrid Electric Powertrain

- Air Compressor
- Fuel Pump: Solid, liquid, gas
- Thermoelectric Multi-Fuel Combustor
- Electric Propulsion Motor
- Transmission
- Gear Box & Differential
- Radiator
- Electric Power Conditioning & Control
  - 440V
  - 12V
- Environmental Energy Storage (Batteries or Ultracapacitors)
  - 12V
- Vehicle Electrical System
  - Driver Demand
- Coolant Pump
Vehicular Thermoelectric Application Possibilities

Near Term (3-5 yrs)
- Thermoelectric Generator providing nominal 5-6% fuel economy gain augmenting smaller alternator
- “Beltless” or more electric engines
- Thermoelectric HVAC augmenting smaller A/C

Mid Term (6-15 yrs)
- Thermoelectric Generators installed in diesel or gasoline engine exhaust
  - 55% efficient heavy duty truck engine
  - 50% efficient light truck, auto
- Thermoelectric Generators and HVAC w/o alternators or A/C
- Aluminum/Magnesium frame & body replacing steel (Process waste heat recovery) mass market cars

Long Term (16-25 yrs)
- 35% efficient Thermoelectrics w 500 °C ∆T
  - Replace Internal Combustion Engine (ICE)
  - Dedicated combustor burns any fuel