Potential of Thermoelectrics for Occupant Comfort and Fuel Efficiency Gains in Vehicle Applications

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Overview

Background on barriers to broader usage of thermoelectrics

TED heating/cooling product roadmap
- First application of thermoelectric devices in passenger vehicles- Amerigon's Climate Controlled Seat (CCS)
- Liquid to liquid heater/cooler for cooling electronics
- Liquid to air heat exchanger for supplemental heating/cooling passenger cabin

Waste heat recovery using thermoelectrics to increase fuel efficiency

Summary and conclusions
Background on Barriers to the Broader Usage of Thermoelectrics
Commercial Interest in Thermoelectrics

Solid-state cooling, heating and power generation

Small, light-weight. Potentially very reliable and rugged

Electrically powered with very few (or no) moving parts

Distributed (and spot) cooling/heating/temperature control

No gaseous pollutants
What Has Limited Usage?

Efficiency has been ¼ that of 2 phase refrigerants
- Inadequate for many high power applications
- Limits usage to small, spot coolers and controllers
- Too inefficient for most electronic cooling

Thermal performance has been low
- Volume and weight too great at high power levels
- Form factor not readily adaptable to some application needs
- Poor interface to high power density applications

Lack of design knowledge and effective simulation tools
- Performance often poorer than predicted
- Characteristics and hence response, can be a strong function of operating conditions
### Sources of TE System Performance Increase

#### Materials
- BiTe Thermoelectrics (1960s)
- Heterostructures (2000-2002) | Baseline +70 to 160%

#### Materials/Design
- Incremental improvements (1960-2002) | 5 to 15%
- Ancillary materials and components (1960-2002) | 5 to 10%

#### Thermodynamic Cycle
- Isolated Element (2000-2002) | 100 to 120%
- Convection (2001-2002) | 30 to 80%

#### Power Density
- Sintered micropower (2002) | Up to 25 X Increase
- Heterostructure (2001) | 30 to 300 X Increase
Product Roadmap for Thermoelectric Heating/Cooling

Current applications:
- Amerigon's CCS
- Cooling electronics using liquid to liquid TEDs
- Supplemental heating and cooling using liquid to air TEDs
- Spot cooling using air to air TEDs

Long term goal:
- Primary HVAC systems
Product Roadmap: Amerigon’s CCS

MTM SEAT TECHNOLOGY
MICRO- THERMAL MODULE

HEAT EXCHANGER

COOLED OR HEATED AIR EXITS TO SEAT CUSHION

WASTE AIR EXITS SEAT

PELTIER CIRCUIT

AIR DISTRIBUTION DETAIL

PERFORATED LEATHER

DISTRIBUTION LAYER

SCRIM MATERIAL

CHANNEL MOLDED IN FOAM

ECU-ELECTRONIC CONTROL MODULE

CONTROL SWITCH
Amerigon Current CCS™ Vehicle Lines

- 2007 Escalade (ESV, EXT)
- 2006 Buick Lucerne
- 2006 Lincoln Zephyr
- Hyundai Equus*
- Lexus LS 430*
- Infiniti (Q45, M45)
- Mercury Monterey
- Toyota Century
- Nissan Cima
- Nissan Fuga
- Infiniti (Q45, M45)
- Toyota Century
- Hyundai Equus*
- Lincoln LS
- Lincoln Navigator
- Lincoln Navigator
- Lincoln Navigator
- Lincoln Aviator
- Toyota Century

* Four Seat Systems
**Product Roadmap: Liquid to Liquid TED for Cooling Electronics**

1. The device shall exhibit thermal efficiencies at least 50% greater than that of conventional TE technology;

2. TE material usage shall be at most 25% that of commercial TE modules;

3. The device shall be readily manufactured and have the prospect of being low cost, compact and minimum weight;

4. The design shall incorporate electrical redundancy;

5. The design shall be scalable to larger and smaller sizes between 50 and 5,000 watt thermal capacity.
Product Design

Fluids and Current Paths

Heat Exchanger
TED Subassembly

TE element located between heat exchangers

Fluid duct connecting heat exchangers

Heat exchangers (26 Total)

Breadboard subassembly.
Power Density Characteristics

TE Performance (DTh = DTc = 15C)
Modeling Inputs (Properties)
Modeling Inputs (Properties)
Modeling Inputs (Properties)

- **TEMPERATURES**
  - Ambient temperature: 42 °C
  - Hot inlet temperature: 41 °C
  - Cold inlet temperature: 38 °C
  - Hot DT: 10 °C
  - Cold DT: 8 °C
  - Total hot mass flow: 221 cfs
  - Total cold mass flow: 20 cfs

- **TE INFORMATION**
  - # of elements per stack: 25
  - TE material: Bi2Te3
  - Seebeck coefficient: 0.0002 V/K
  - Electrical resistivity: 0.001 ohm-cm
  - Thermal conductivity: 15 W/mK
  - ZT: 0.8
  - TE elect. inter. resist.: 2e-010 ohm - m²

- **FLUID PROPERTIES**
  - Hot fluid:
    - Water: density
    - Thermal conductivity: 0.613 W/mK
    - Dynamic viscosity: 0.000555 Ns/m²
  - Cold fluid:
    - Water: density
    - Thermal conductivity: 0.613 W/mK
    - Dynamic viscosity: 0.000555 Ns/m²
    - Specific heat: 4179 J/kgK
    - Density: 0.613 W/mK

- **HEX DIMENSIONS**
  - Plate thickness: 0.00508 cm
  - Side thickness: 0.00508 cm
  - TE pad thickness: 0 cm

- **OTHER**
  - Pump efficiency: 0.5
  - Thermal interfacial resistance: \(1e-007 \text{ (m}^2\text{K/W)}\)
  - English Units
    - Metric Units

- **SAVE CONDITIONS**
  - Filename

- **LOAD CONDITIONS**
  - Newport cond

- **SOLDER**
  - Bulk electrical resistivity:
    - Metric units: 656.0 ohm-cm
    - English units: 3e-009 ohm-cm²
  - Bulk thermal conductivity:
    - Metric units: 52.4 W/mK
    - English units: 421.5 W/mK
  - Thickness:
    - Metric units: 0.0051 cm
    - English units: 0.0005 cm

- **BRAZE**
  - Bulk electrical resistivity: 2.2e-006 ohm-cm
  - Electrical interfacial resistivity: 3e-009 ohm-cm²
  - Bulk thermal conductivity: 421.5 W/mK
  - Thickness: 0.0076 cm
Modeling Inputs (Properties)

- **Temperatures**
  - Ambient temperature: 42°C
  - Hot inlet temperature: 41°C
  - Cold inlet temperature: 38°C
  - Hot DT: 10°C
  - Cold DT: 6°C

- **TE Information**
  - # of elements per stack: 25
  - TE material: Bi2Te3
  - Seebeck coefficient: 0.0002 V/K
  - Electrical resistivity: 0.001 ohm-cm
  - Thermal conductivity: 1.5 W/mK
  - TE elect. inter. resist.: 2e-010 ohm-m

- **Fluid Properties**
  - Hot fluid:
    - Density: 997 kg/m³
    - Thermal conductivity: 0.613 W/mK
    - Dynamic viscosity: 0.0008855 Ns/m²
    - Specific heat: 4179 J/kgK
  - Cold fluid:
    - Density: 997 kg/m³
    - Thermal conductivity: 0.613 W/mK
    - Dynamic viscosity: 0.0008855 Ns/m²
    - Specific heat: 4179 J/kgK

- **Other**
  - Pump efficiency: 0.5
  - Thermal interfacial resistance: 1e-007 (m²)K/W

- **Hex Dimensions**
  - Plate thickness: 5508 cm
  - Side thickness: 5508 cm
  - TE pad thickness: 0.6 cm

- **Save Conditions**
  - Filename: newport_cond

- **Load Conditions**
  - Jaun impoverishment: 0.006 cm

- **Solder**
  - Bulk electrical resistivity: 650e-005 ohm-cm
  - Electrical interfacial resistivity: 3e-009 ohm-cm²
  - Bulk thermal conductivity: 52.4 W/mK
  - Thickness: 0.0051 cm

- **Braze**
  - Bulk electrical resistivity: 2.2e-006 ohm-cm
  - Electrical interfacial resistivity: 3e-008 ohm-cm²
  - Bulk thermal conductivity: 421.5 W/mK
  - Thickness: 0.0076 cm
Modeling Inputs (Properties)
Modeling Inputs (Dimensions)
Modeling Inputs (Dimensions)
# Modeling Inputs (Dimensions)

![Modeling Inputs (Dimensions)](image)

## DESIGN VARIABLES

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>fin density</td>
<td>18.5 fins/cm</td>
</tr>
<tr>
<td>fin height</td>
<td>0.18 cm</td>
</tr>
<tr>
<td>fin length</td>
<td>0.625 cm</td>
</tr>
<tr>
<td>heat exchanger width</td>
<td>1.5 cm</td>
</tr>
</tbody>
</table>

## DESIGN VARIABLES (cold-side)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>fin density</td>
<td>18.5 fins/cm</td>
</tr>
<tr>
<td>fin height</td>
<td>0.18 cm</td>
</tr>
<tr>
<td>fin length</td>
<td>0.625 cm</td>
</tr>
<tr>
<td>heat exchanger width</td>
<td>1.5 cm</td>
</tr>
</tbody>
</table>

## MODELING Inputs (Dimensions)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE leg width</td>
<td>1.2 cm</td>
</tr>
<tr>
<td>TE leg length</td>
<td>1.08 cm</td>
</tr>
<tr>
<td>TE leg thickness</td>
<td>0.08 cm</td>
</tr>
<tr>
<td>total elements</td>
<td>875</td>
</tr>
<tr>
<td>total desired flow</td>
<td>20 (cm^3)/s</td>
</tr>
</tbody>
</table>

## OUTPUTS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP</td>
<td>0</td>
</tr>
<tr>
<td>mass flow stack hot</td>
<td>0 g/s</td>
</tr>
<tr>
<td>mass flow stack cold</td>
<td>0 g/s</td>
</tr>
<tr>
<td>input power stack</td>
<td>0 W</td>
</tr>
<tr>
<td>total voltage</td>
<td>0 V</td>
</tr>
<tr>
<td>power density</td>
<td>0 W/(cm^3)</td>
</tr>
<tr>
<td>maximum current</td>
<td>0 A</td>
</tr>
<tr>
<td>accessory power</td>
<td>0 W</td>
</tr>
<tr>
<td>pressure drop - hot</td>
<td>0 Pa</td>
</tr>
<tr>
<td>pressure drop - cold</td>
<td>0 Pa</td>
</tr>
<tr>
<td>total TE volume</td>
<td>0 cm^3</td>
</tr>
<tr>
<td>total hex volume</td>
<td>0 cm^3</td>
</tr>
</tbody>
</table>
Modeling Outputs

[Diagram showing design variables and outputs for a system, with values for fin density, TE leg length, TE leg area, and total desired flow.]
TE Subassembly

TE element location between heat exchangers

Fluid duct connecting heat exchangers

Heat exchangers (26 Total)

Breadboard subassembly.
Infrared Camera Image of TED Subassembly
Temperature Profile of TED Subassembly (using IR camera)
25 Stack Performance

- Data: \( \Delta \) \( dT_c = 10 \), \( dT_h = 5 \), \( T_{cin} = T_{cih} = 30 \)
- Data: \( \bullet \) \( dT_c = 10 \), \( dT_h = 20 \), \( T_{cin} = T_{cih} = 40 \)
- Data: \( \Box \) \( dT_c = 25 \), \( dT_h = 12.5 \), \( T_{cin} = T_{cih} = 40 \)
- Data: \( \triangle \) \( dT_c = 25 \), \( dT_h = 30 \), \( T_{cin} = T_{cih} = 35 \)
- Model: \( \Delta \) \( dT_c = 10 \), \( T_{cin} = T_{cih} = 30 \)
- Model: \( \bullet \) \( dT_c = 10 \), \( T_{cin} = T_{cih} = 40 \)
- Model: \( \Box \) \( dT_c = 25 \), \( T_{cin} = T_{cih} = 40 \)
- Model: \( \triangle \) \( dT_c = 25 \), \( T_{cin} = T_{cih} = 35 \)
## Properties Comparison of Standard and Stack Design TE Modules

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard Module</th>
<th>Stack Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal cooling power at $\Delta T_c = 10^\circ C$; $\Delta T_h = 5^\circ C$</td>
<td>4.20</td>
<td>3.00</td>
</tr>
<tr>
<td>TE material weight (grams)</td>
<td>125.0</td>
<td>125.0</td>
</tr>
<tr>
<td>Heat Exchanger weight (grams)</td>
<td>290.0</td>
<td>129.4</td>
</tr>
<tr>
<td>Weight of other materials: substrates, sealants, wiring</td>
<td>485.3</td>
<td>146.8</td>
</tr>
<tr>
<td>Total subsystem weight (grams)</td>
<td>485.3</td>
<td>146.8</td>
</tr>
<tr>
<td>Volume (liters)</td>
<td>0.0616</td>
<td>0.0521</td>
</tr>
<tr>
<td>Power density (watts/liter)</td>
<td>1057</td>
<td>1250</td>
</tr>
<tr>
<td>Specific cooling power (watts/gram)</td>
<td>0.134</td>
<td>0.443</td>
</tr>
<tr>
<td>Peak efficiency (COP)</td>
<td>2.25</td>
<td>4.20</td>
</tr>
</tbody>
</table>
Liquid to Liquid TED Design Objectives

1. The device shall have a nominal thermal pumping capacity of 3,500 watts in cooling mode.
2. The system shall be capable of cooling 0.19 Liters/second of H2O by 6ºC.
3. Electrical power consumption shall be less than 1,000 watts.
4. Maximum weight shall be 4.7 Kg.
5. Maximum volume shall be 2.0 Liters.
3500 W Cooler System
Comparison of Computed and Experimental Results for 3,500W Cooler

Experiment, 0.158 L/s
Theory
Experiment, 0.189 L/s
Theory
# System Performance Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Final Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal cooling power at $\Delta T_c = 6^\circ C$ (watts)</td>
<td>3500</td>
</tr>
<tr>
<td>System weight (Kilograms)</td>
<td>4.4</td>
</tr>
<tr>
<td>Weight of other materials (shunts, substrates, sealants, wiring) (Kilograms)</td>
<td>0</td>
</tr>
<tr>
<td>Total system weight (Kilograms)</td>
<td>4.6</td>
</tr>
<tr>
<td>Volume (Liters)</td>
<td></td>
</tr>
<tr>
<td>Power density (Kilowatts/liter)</td>
<td>2.26</td>
</tr>
<tr>
<td>Specific cooling power (watts/gram)</td>
<td>0.76</td>
</tr>
<tr>
<td>Peak efficiency (COP)</td>
<td>4.20</td>
</tr>
</tbody>
</table>
Liquid to Air TED

Designed to provide rapid time to comfort for vehicle occupants

Performance targets:

- In heating mode, pumps heat from liquid to air achieving a nominal COP of 2.5 (2500 watts @ 1000 watts electrical input power)
- In cooling mode, rejects heat from air to the liquid and achieves a COP of 1.5 (1500 watts of cooling @1000 watts electrical input power)
- Nominal $\Delta T$ in air – 20C lift in heating and 15C depression in cooling
Liquid-air thermoelectric heater/cooler
Liquid to Air Heating Performance

-20°C Air, -20°C Liquid, Delta T Air = 18.5, Liquid Flow 10 L/ min, Air Flow 190 CFM

COP of 2.5 predicted and experimentally validated
Waste Heat Recovery Using Thermoelectrics to Increase Fuel Efficiency
Thermal Management.
Thermoelectric Generator.
System Modeling

Electrical power output of the TGM (for NEDC)

Detroit, Michigan- DEER 2006
August 20-24, 2006
Summary & Conclusions

Amerigon’s Climate Control Seat has validated the application of thermoelectrics in the automotive industry with over 1,000,000 devices sold in 2005 and scheduled volume increases in the next several years.

New applications are in development at Amerigon and BSST that achieve improved performance by employing thermal isolation and high density design and construction:

1. Performance is improved by about 90% by employing thermal isolation with thermodynamic cycle.
2. TE material usage is reduced by a factor of 4 by:
   a) Using stack design
   b) Design optimization to reduce unnecessary parasitic losses

Compact, light weight, efficient cooler/heater/temperature devices can be produced with up to at least 5,000 thermal watt output.

A thermoelectric waste heat recovery has been modeled to demonstrate 10% fuel economy improvement and key systems will be built and tested this year.