A MODEL BASED APPROACH TO EXHAUST HEAT RECOVERY USING THERMOELECTRICS

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Objective

- Investigate potential for generating electricity from exhaust waste heat in a hybrid vehicle using thermoelectrics.

Why Exhaust Heat?

- Of the available energy in fuel, only about $1/5^{th}$ and $1/3^{rd}$ is converted into useful work at part load and full load conditions, respectively. The rest of the energy is primarily wasted.

Temperature and energy content of exhaust gas is high.
- Exhaust gas temperature can reach as high as $900^\circ C$ with potential for high cycle efficiency.
Why Thermoelectrics?

• Direct conversion of heat into electricity with few or no moving parts.
• Less components needed thus less packaging & weight constraint compared to a Rankine power generation cycle.
• Potentially reliable and rugged device.
• No environmental side effects.

Where is it used?

• Satellites, space probes
• Remote gas and oil pipelines for powering instruments
• Military application where silent power generation is a priority
Why Not in Automobiles?

- Low conversion efficiency.
- High cost of thermoelectric material.
- Additional weight/volume penalty for automotive application.

Why Now?

- Increased need to reduce fuel consumption.
- Higher price of fuel renders technology that was too expensive previously much more cost competitive now.
- Recent advancements in nanotechnology and semiconductor physics holds promise more than ever before.
- Dedicated companies and government agencies working towards better understanding and implementation of the technology.
Thermoelectrics Fundamentals

- Thermoelectric generators, similar to thermocouples, are based on Seebeck effect.
- Two dissimilar conductors, joined end to end, when subjected to a temperature differential at the two ends produces a electrical potential (voltage).
- Thermoelectric generators work on the same principle using p and n type semiconductor material. Voltage is generated and current flows from n to p.
TE Device Geometry

Side Sectional View

Front Sectional View

Coolant In
Coolant Out

Exhaust In
Exhaust Out

Thermoelectric Material Lined Channels

Channel Length

Channel Width

A “9” Channel TE Generator

TE thickness
Electric Network Analog of GT-Power TE Model

Exhaust Gas

Temperature Profile

Coolant

$R_A = X_A/4K_A A_1$

$R_B = X_B/2K_B A_1$

$R_C = X_C/2K_C A_1$

$R_D = X_D/2K_D A_1$

$R_E = Y_A/2K_A A_2$

$R_I = 1/h_i A_1$

$Y_A$

$T_H (Source)$

$T_C (Source)$

$T_G$

$T_F$

$R_o = 1/h_o A_1$
Heat Transfer and Power Generation in TE material

\[ Q_H = K\Delta T + \alpha T_H I - \frac{1}{2} I^2 R_i \]

\[ Q_C = K\Delta T + \alpha T_C I + \frac{1}{2} I^2 R_i \]

Power
\[ = Q_H - Q_C \]
\[ = (\alpha\Delta T)I - I^2 R_i \]
\[ = V_{oc} I - I^2 R_i \]
\[ = I(R_i + R_L)I - I^2 R_i \]
\[ = I^2(R_i + R_L) - I^2 R_i \]
\[ = I^2 R_L \]
Key Model Features

- GT-Power solver used
- Commercially available thermoelectric material
- Temperature dependent TE material property
- Prescribed cold junction temperature
- No thermal contact resistance
- No heat loss from the device to ambient
- Steady state solution uses cycle average mass flow rate and gas temperature as input
- Transient solution uses time dependent mass flow rate and gas temperature as input
• Under identical operating conditions and material properties, predicted results are compared against theoretical values for a single p-n junction (Direct Energy Conversion” – Stanley W. Angrist, 4th Ed., Allyn and Bacon, Inc., 1982)
System Layout

• The TE generator is placed downstream of the catalytic converter on the exhaust line.
• This location will not interfere with emission control strategy.
• Benefits from the exothermic reaction in the catalytic converter.
Steady State Design Optimization

- Four factors were identified that affect the performance of a TEG of a given material property and a given boundary condition:
  - Channel Length, L
  - Channel Number, N
  - Channel Width, W
  - TE Thickness, t

<table>
<thead>
<tr>
<th>Factor</th>
<th>Min Range</th>
<th>Max Range</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Length (mm)</td>
<td>100</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>Channel Number</td>
<td>5</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>Channel Width (mm)</td>
<td>5</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>TE Thickness (mm)</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

- Channel width (W) is the most sensitive factor.
Design Optimization

- TE mass, pressure drop, and response time were evaluated as constraints.
- Time constant as a measure of response time was determined from lumped heat capacity
  \[ \tau = \frac{c \rho V}{h A} \]
- 2.5L Atkinson Engine in Escape Hybrid vehicle is used.

<table>
<thead>
<tr>
<th>Drive Condition</th>
<th>Mass Flow Rate (kg/hr)</th>
<th>Temperature (deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway</td>
<td>56.5</td>
<td>638</td>
</tr>
<tr>
<td>City</td>
<td>19.5</td>
<td>570</td>
</tr>
</tbody>
</table>
Design selection flowchart

Parameter | Design 1 | Design 2 | Design 3
---|---|---|---
Power | Medium | High | Low
TE Mass | Medium | High | Low
Pressure Drop | Medium | High | Low
\(N\) | 20 | 15 | 25
\(L\) (mm) | 150 | 250 | 100
\(W\) (mm) | 5 | 5 | 5
\(t\) (mm) | 3 | 3 | 2

Selected designs

Final design
Power versus TE Mass: Steady State Highway Drive Condition

Peak Power

Design 2

Design 1

Design 3

(a) 5mm X 5mm Channel

Power (W)

TE Mass (g)

N = 5, L = 100
N = 10, L = 100
N = 15, L = 100
N = 20, L = 100
N = 25, L = 100
N = 30, L = 100
N = 5, L = 150
N = 10, L = 150
N = 15, L = 150
N = 20, L = 150
N = 25, L = 150
N = 30, L = 150
N = 5, L = 200
N = 10, L = 200
N = 15, L = 200
N = 20, L = 200
N = 25, L = 200
N = 30, L = 200
N = 5, L = 250
N = 10, L = 250
N = 15, L = 250
N = 20, L = 250
N = 25, L = 250
N = 30, L = 250
N = 5, L = 300
N = 10, L = 300
N = 15, L = 300
N = 20, L = 300
N = 25, L = 300
N = 30, L = 300
Power versus Pressure Drop: Steady State Highway Drive Condition

Peak Power

Design 1

Design 2

Design 3

Log Pressure Drop (kPa)

5mm X 5mm Channel

(b)

Power (W)
Power versus Response Time: Steady State Highway Drive Condition

- **Design 1**
- **Design 2**
- **Design 3**

- **Peak Power**

Power (W) vs. Time Constant (s) for different values of N (number of elements) and L (length of channel):

- N = 5, L = 100
- N = 10, L = 100
- N = 15, L = 100
- N = 20, L = 100
- N = 25, L = 100
- N = 30, L = 100
- N = 5, L = 150
- N = 10, L = 150
- N = 15, L = 150
- N = 20, L = 150
- N = 25, L = 150
- N = 30, L = 150
- N = 5, L = 200
- N = 10, L = 200
- N = 15, L = 200
- N = 20, L = 200
- N = 25, L = 200
- N = 30, L = 200
- N = 5, L = 250
- N = 10, L = 250
- N = 15, L = 250
- N = 20, L = 250
- N = 25, L = 250
- N = 30, L = 250
- N = 5, L = 300
- N = 10, L = 300
- N = 15, L = 300
- N = 20, L = 300
- N = 25, L = 300
- N = 30, L = 300
Power versus TE Mass: Steady State City Drive Condition

- Higher power generation potential exists with reduced number of channels

- This will lead to excessive backpressure under high mass flow

![Graph showing power versus TE mass for different designs and channel configurations.](attachment:graph.png)
Energy Balance in a TEG

Design 1: \( L = 150, \ N = 20, \ W = 5 \text{ mm}, \ t = 3 \text{ mm} \)

\[ T_h = 263^\circ C \]
\[ 321^\circ C \]
\[ T_c = 100^\circ C \]

Power = 325 W
Efficiency = 5.97%

Th = 263\(^\circ\) C
Tc = 100\(^\circ\) C

321\(^\circ\) C
4,827 W

Heat Reject
5,120 W

Carnot Efficiency = \( (T_h - T_c) / T_h = 30.4\% \)

Steady State Highway

570\(^\circ\) C
3,130 W

T_h = 157\(^\circ\) C

T_c = 100\(^\circ\) C

239\(^\circ\) C
1,193 W

Heat Reject
1,885 W

Carnot Efficiency = \( (T_h - T_c) / T_h = 15.3\% \)

Steady State City

- Low thermal efficiency is the primary reason why TE use is limited.
- Even though thermal input is free of cost in waste heat recovery, large amount of TE material (cost) is needed for meaningful power.
Transient Analysis

Cycle Averaged Power = 330 W
Cycle Averaged Power = 78 W
Cycle Averaged Pressure Drop = 4.01 kPa
Cycle Averaged Pressure Drop = 1.03 kPa

Design 1: Highway Drive Cycle
Design 1: City Drive Cycle
Transient Analysis

- So far, TE device was decoupled from downstream exhaust system. In reality this is not the case.

- Moreover, it is important to take into consideration the added backpressure the engine will be subjected to when a thermoelectric generator is placed in an exhaust system.

- To do this, an orifice size was first calibrated that replicates the pressure drop of the exhaust system.

- Next this orifice was placed at the outlet of the thermoelectric device to impose exhaust system backpressure.
Transient Analysis

Pressure Drop: Highway Drive Cycle

Pressure Drop: City Drive Cycle

If the added backpressure is not acceptable then a less restrictive design will be selected at the cost of lower electricity generation.
## Transient versus Steady State Analysis

### Design comparison under highway drive conditions

<table>
<thead>
<tr>
<th></th>
<th>Design 1</th>
<th></th>
<th>Design 2</th>
<th></th>
<th>Design 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tran</td>
<td>SS</td>
<td>Tran</td>
<td>SS</td>
<td>Tran</td>
<td>SS</td>
</tr>
<tr>
<td>TE Mass (kg)</td>
<td>1.39</td>
<td></td>
<td>1.73</td>
<td></td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Power (W)</td>
<td>330</td>
<td>325</td>
<td>391</td>
<td>380</td>
<td>248</td>
<td>230</td>
</tr>
<tr>
<td>Backpressure (kPa)</td>
<td>5.59</td>
<td>3.21</td>
<td>10.24</td>
<td>7.21</td>
<td>3.92</td>
<td>1.75</td>
</tr>
</tbody>
</table>

### Design comparison under city drive conditions

<table>
<thead>
<tr>
<th></th>
<th>Design 1</th>
<th></th>
<th>Design 2</th>
<th></th>
<th>Design 3</th>
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</tr>
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<tr>
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<tr>
<td>TE Mass (kg)</td>
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<td></td>
<td>1.73</td>
<td></td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Power (W)</td>
<td>78</td>
<td>52</td>
<td>94</td>
<td>63</td>
<td>56</td>
<td>35</td>
</tr>
<tr>
<td>Backpressure (kPa)</td>
<td>1.55</td>
<td>0.32</td>
<td>2.78</td>
<td>0.73</td>
<td>1.05</td>
<td>0.2</td>
</tr>
</tbody>
</table>

More unsteady the input condition (city vs. highway), more the difference between steady state and transient results
Cold Junction Temp Effect

- Power increases almost linearly with drop in cold junction temp.
- A dedicated radiator is needed to take advantage of this.
- This will add cost, weight and complexity to the system.
Summary

- It is technically feasible to use thermoelectrics to generate electricity from exhaust waste heat.
- The model predicts the potential of 300 W – 400 W generation for EPA highway drive cycle with 2.5L hybrid Atkinson engine.
- Much lower power output is predicted for EPA city cycle.
- The thermoelectric device when placed on the exhaust system increases net backpressure on the engine although downstream exhaust system backpressure is reduced due to cooling effect.
- Backpressure increase will go against any fuel economy benefits derived from the electrical power generation in the TE device.
- More unsteady the input condition, more the difference between steady state and transient results.
- A dedicated radiator can increase TE output.
APPENDIX
Thermoelectrics Fundamentals

- Figure of Merit of a thermoelectric material is defined as
  \[ Z = \frac{\alpha^2 \sigma}{\lambda} \]
  Where, \( \alpha \) is Seebeck coefficient, \( \sigma \) is electrical conductivity and \( \lambda \) is thermal conductivity.
- \( Z \) is more commonly expressed as the *dimensionless figure of merit* \( ZT \) by multiplying it with the average temperature, \( \frac{T_H + T_C}{2} \).
- \( ZT \) is proportional to the efficiency of the device. Values of \( ZT = 1 \) are considered good.
- \( ZT \) is convenient for comparing device performances using different materials.
Mathematical Formulation


• The thermal efficiency is maximized by choosing an optimum ratio of load resistance to internal resistance,
  \[ m = \frac{R_L}{R_i} \]

• This is derived to be, \( m^* = (1 + ZT)^{1/2} \)

• Heat flowing into and out of hot and cold junctions are,
  \[ Q_H = K\Delta T + \alpha T_H l - (1/2)l^2R_i \]
  \[ Q_C = K\Delta T + \alpha T_C l + (1/2)l^2R_i \]

  Where \( K \) is thermal conductance and \( l \) is current. Note that the first term is the flow of heat due to temperature gradient, second term is Peltier effect and the third term is the Joule effect.

• The difference of heat going into hot junction and coming out of cold junction is the power produced,
  \[ P = Q_H - Q_C \]
Mathematical Formulation

- Alternatively, power generated can also be defined as,
  \[ P = I^2R_L \]
  where current is found from,
  \[ I = \alpha \Delta T / (R_i + R_L) \]
- Thermal efficiency, the ratio of power generated to heat supplied is,
  \[ \eta = P / Q_H \]
- In terms of junction temperatures the thermal efficiency is defined as,
  \[ \eta = \left[ \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + (T_C / T_H)} \right] \frac{T_H - T_C}{T_H} \]

- The second term is the Carnot efficiency and higher value of \( ZT \) leads to higher efficiency for a given hot and cold side temperature
Modeling Approach & Assumptions

- A TE generator is made of a large number of TE elements. It is not practical to solve for each of them individually.
- A group of elements are lumped together for practicality. Each lump has its own temperature, voltage and current. One group of such couples are referred to as a segment.
- Study was done to determine least number of segments that provided sufficient accuracy.
- Device efficiency versus TE segments was compared.
- 3 segments were found to be adequate and used in this work