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Thermoelectric Energy Harvesting

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Recent Progress in Thermoelectric Power Generation Systems for Commercial Applications

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ABSTRACT

Thermoelectric (TE) devices are solid state heat engines that directly convert thermal to electrical power (Seebeck Effect) and the reverse, electrical to thermal power (Peltier Effect). The phenomena were first discovered over 150 years ago and until recently have been more of a scientific curiosity than a practical technology of commercial interest. However, as governments impose regulations on greenhouse gas emissions and as the long-term availability of fossil fuels is questioned, alternative technologies, including thermoelectrics, are being explored to meet the challenges that arise from these new conditions.

Amerigon, the parent of BSST, is the largest supplier of thermoelectric (TE) devices to the automotive market. Over the last ten years BSST has been developing TE technology for the transportation market. Recent advancements at the system level made by BSST and improvements in TE materials made by several organizations indicate a path to improved performance and economic feasibility. This report discusses development of TE Generator (TEG) technology and of a TEG system installed in the power train of internal combustion engines for the purpose of converting waste heat to electric power. Our work has been made possible, in part, through sponsorship by the United States Department of Energy Office of Vehicle Technologies. The BMW Group, Ford Motor Company and Faurecia are partners in the BSST-led program.

INTRODUCTION

Global pressure to reduce greenhouse gasses created through the combustion of fossil fuels continues to rise. The EU is leading the way in sustainable emissions' reductions[i]. Collectively the member states decided in 2008 to cut greenhouse gas emissions to at least 20% below 1990 levels by 2020. In doing so, targets have been set to meet 20% of the EU's energy needs from renewable sources and to move towards 20% energy efficiency improvement. Specifically, the EU car market regulations include requirements for CO_2 emissions levels to be less than 95 grams/CO_2/km by 2020. In the United States, new CAFE levels slated for 2020 have been accelerated to begin in 2016. Additionally, the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) recently announced[ii] a first-ever program to reduce greenhouse gas (GHG) emissions and improve fuel efficiency of medium- and heavy-duty vehicles, such as the largest pickup trucks and vans, semi trucks, as well as requirements for all related sizes of work trucks and buses. The proposed NHTSA standards represent an average per-vehicle improvement in fuel consumption of 15 percent for diesel vehicles and 10 percent for gasoline vehicles, compared to a common baseline.

Because many CO_2 emissions reduction technology options have been implemented and the prospect of a single new emissions technology "silver bullet" are not apparent, OEMs are evaluating a range of technology options that collectively result in achieving regulatory compliance. Thermoelectric technology is being evaluated by OEMs worldwide for converting vehicular waste heat into storable electrical power.

BSST and our program partners began work under a US DOE sponsored program[iii] to convert exhaust gas waste heat to power using a thermoelectric generator (TEG) in 2005. The program is scheduled to conclude in 2011 with the evaluation of TEG systems in vehicles at BMW and Ford. The program objective is to offload shaft power to the vehicle alternator with a TEG to increase fuel efficiency by 10%.

THERMOELECTRIC MATERIALS

Traditional TE engines are comprised of n and p type elements with electrical and thermal connectors as shown in Figure 1 below.

In selecting TE materials, one aims to maximize the TE figure of merit, or Z, where $Z = \alpha^2/\lambda\rho$, and α is the TE material Seebeck coefficient, λ is the thermal conductivity and ρ is the electrical resistivity. Typical TE material performance as a function of temperature for n and p type materials is shown in Figure 2 below[iv]. The single most expensive constituent of a TEG is TE material.

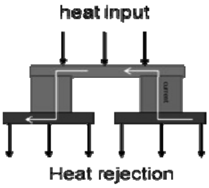

Figure 1: Traditional TE Engine

Therefore, designers must choose carefully TE materials both to maximize efficiency and be highly cost effective. In part, these objectives are achieved by arranging TE materials so as to have peak effectiveness in the intended range of operation, and maximize material power density.

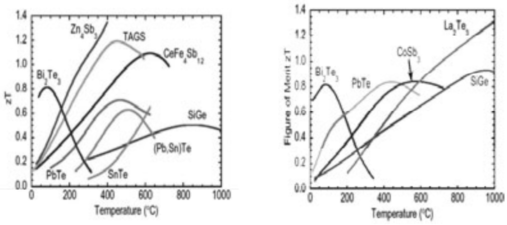

Figure 2: TE Material Properties

TE ENGINE DESIGN

Traditional TE modules have TE couples integrated into the module such that each TE element has the same thickness and electrical current passes from one couple to another similar to the array shown in Figure 3.

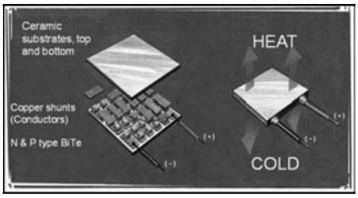

Figure 3: Traditional Module Design

This configuration does not easily accommodate the use of TE elements of different thickness and area. It is also difficult to control thermally induced stresses when the elements are of equal height but have different thermal expansion coefficients. This becomes a significant constraint in power generation applications where temperature excursions are large. Figure 4 shows an alternative configuration that more readily accommodates elements of different thickness and cross sectional area

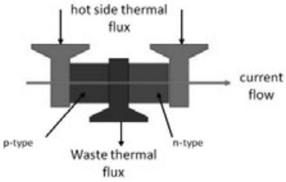

Figure 4: BSST Stack Design

Each TE element (alternating between p- and n- legs) is arranged between thermal/electrical connectors. The connectors provide an electrical path from one TE element to another completing the necessary TE p-n couple. The connectors also provide a thermal path from the fluid-carrying channels to the TE elements.

Electrical current runs parallel to the heat source and sink surfaces in this configuration, allowing the integration of the TE material with multiple geometric degrees of freedom, and other important design attributes as discussed by Crane[v]. Further, this design allows high density engine design and thermal isolation in the direction of flow, as discussed by Bell[vi],[vii]. In order to enhance the performance of the TEG, the proprietary stack design concepts have been implemented.

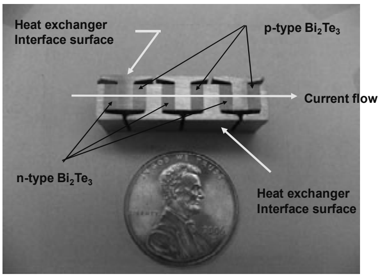

Figure 5: BiTe Stack Assembly

An example of a TE engine subassembly built using Bi_2Te_3 TE material is shown below in Figure 5. This subassembly produces one watt of power at a ΔT of 205^{0}C.

VEHICLE SYSTEM ARCHITECTURE

The system architecture employs a direct, in-line cylindrical heat exchanger. The system architecture is simplified to more readily enable first commercialization of the technology. The architecture is shown in Figure 6.

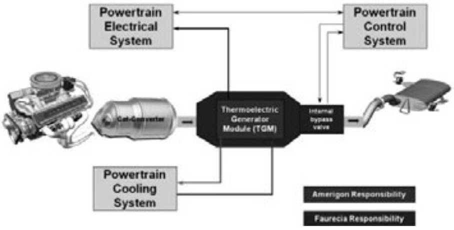

Figure 6: TEG Vehicle System Architecture

TEG MODELING, DESIGN AND CONSTRUCTION

From the start of the DOE sponsored Waste Heat Recovery Program, we sought to optimize the performance of the TEG System at the vehicle level through analysis using Gamma Technologies based bumper to bumper computer model developed by our OEM partners. A comprehensive model of the TEG, developed at BSST in Matlab Simulink, was integrated into the OEM vehicle model to predict TEG system performance as a function of a wide range of system configurations, TEG design parameters and driving conditions.

TEG designers worldwide are working to address three key interfaces that drive TEG power output and efficiency. They are;

1. thermal interface between the hot working fluid or heat source and adjacent TE material,
2. series electrical resistance in the Seebeck circuit and
3. thermal interface between the cold working fluid or heat sink and TE material.

Other important design parameters include;

1. matching TEG output voltage to the vehicle power buss
2. controlling exhaust gas pressure drop through the TEG to limit engine performance degradation,
3. maximizing robustness and manufacturability and

4. minimizing TEG size, weight, volume, and cost.

Initial TEG design and construction was based on a planar array of BSST stack design TE engines arranged between flat plate heat exchangers. This approach demanded tight control of surface flatness and smoothness and that a constant distance between plates be maintained over the entire operating temperature range (necessitating that the TE engine height also be carefully controlled). After prototype construction and test of the flat plate design, a more robust cylindrical configuration was pursued. It was believed that the cylindrical design would provide a comparatively simpler vehicle installation, have lower cost (use less TE material) and be closer to a mass production configuration.

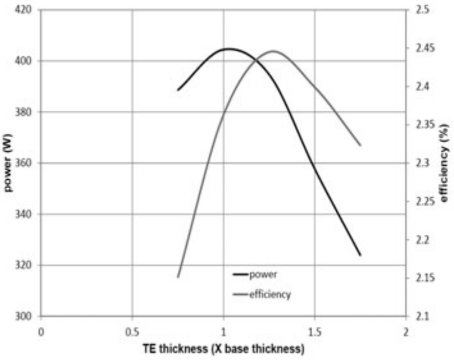

Figure 7: TEG Simulation Result

TE engine models which incorporate temperature dependent TE material properties were developed at BSST. Details of the model have been described previously, and accurately portray the performance of the devices[viii]. The TE engine model was used as a component of the thermal and electrical model of the cylindrical TEG assembly. Typical simulation results for the generator are presented in Figure 7.

The model can be used for simultaneous multivariable optimizations and for parametric performance studies under a range of input conditions. The model includes component and subsystem weights so that the amount of TE material employed can be minimized.

The initial cylindrical prototype TEG design is shown in Figure 8.

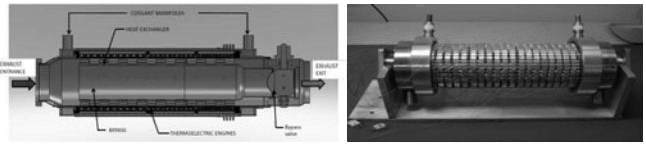

Figure 8: Cylindrical TEG Prototype

Exhaust gas enters from the left, passes through the TEG system, and exits to the right. In normal operation, the valve on the outlet side (right) is closed so that gas is prevented from passing through the central (bypass) region of the heat exchanger subassembly. The valve allows excess exhaust gas flow to bypass the heat exchanger reducing backpressure to within allowable limits. At high flow rates if all the exhaust gas passed through the heat exchanger the backpressure would be above the limit for optimal engine operation and expose the thermoelectric materials to potentially harmful temperatures. The valve, designed and fabricated by program partner Faurecia, has proportional control so that the optimum available thermal power in the exhaust stream can be utilized. The valve position also can be adjusted to prevent the TE system from exposure to the excess temperatures experienced during extreme driving conditions. The thermal power collected by the heat exchanger fins is conducted through the cylinder wall to hot side shunts. The shunts are electrically isolated from the cylinder. Thermal power flows from the hot side shunts through the TE elements to the cold side shunts. Sleeve assemblies transfer waste thermal power to the coolant through tubes which are electrically isolated from the cold side shunts. The coolant enters a manifold at the right side, passes through an array of tubes and is collected at the left before exiting the system. Generally, the coolant is an ethylene glycol water mixture and is part of the vehicle's engine coolant loop.

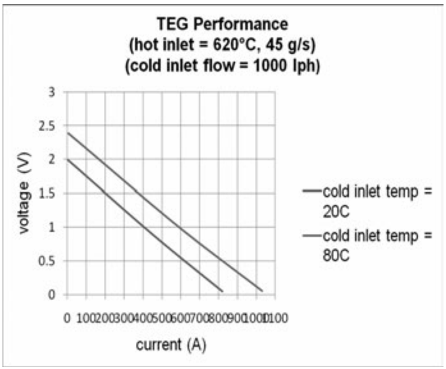

Figure 9: Nominal Voltage/Current Relationship

Electrical power generated by the assembly passes through terminals at the right and left sides of the figure. In the present design, TE engines in each row are electrically in parallel and the rows are electrically in series. Thus the assembly has a series-parallel arrangement, providing a high level of electrical redundancy and increased reliability. The nominal voltage/current characteristics of the device as a function of inlet temperature are shown in Figure 9.

Figure 10 presents three typical TE engines. The high temperature engines, on the left in the figure, operate at the hottest (inlet) temperatures, the mid temperature engines in the middle of the TEG and the low temperature engines near the exhaust exit. The high and mid temperature engines use Half Heusler material segmented with Bi_2Te_3. The low temperature engines use Bi_2Te_3 only. TE element segment lengths were chosen based on modeling analysis and subsystem breadboard tests. The design parameters were chosen so as to operate the Half Heusler and Bi2Te3 materials at internal temperatures which provide efficient performance and reduce degradation from thermal cycling. However, the fabricated assembly exhibited efficiencies, Figure 7, that were lower than predicted due to excessive parasitic losses at the TE element interfaces. Design modifications are currently underway to reduce these losses and thus increase efficiency and total power output.

Figure 10: Typical TE Engines

FUTURE WORK

The US DOE sponsored TEG program concludes in Q3 2011 with the installation and evaluation of TEG equipped exhaust systems in Ford and BMW vehicles. A follow-on program has been suggested, in which the manufacture of TE materials and engines are scaled up in anticipation of first commercialization in the 2015/2016 time period.

ACKNOWLEDGMENTS

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Power Generation Efficiency with Extremely Large Z factor Thermoelectric Material

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ABSTRACT

A recently developed generic model of a thermoelectric power generation system suggests a promising future for cost effective and scalable power generation. The model is based on co-optimizing the thermoelectric module together with the heat sink. Using this model, efficiency at maximum output power is calculated. It is shown that this approaches the Curzon-Ahlborn limit at very large Z values which is consistent with thermodynamic systems with irreversible heat engines. However, this happens only when the thermal resistances of the thermoelectric device with hot and cold heat sinks exactly match. For asymmetrical thermal resistances, the efficiency at maximum output power is different. This is consistent with the very recent results for the thermodynamic engines. Finally, we study the impact of lowering the thermal conductivity of the thermoelectric material or increasing its power factor and how these affect the performance of the thermoelectric power generation system.

INTRODUCTION

Thermoelectric materials are getting more attention and interest due to the emergent need for green technology. The low efficiency of the energy conversion is a concern in many direct thermal to electrical energy conversion applications. Typically, Carnot efficiency is invoked as the maximum theoretical limit when the material figure-of-merit (ZT) goes to infinity. This is analogous to the thermodynamic reversible heat engines and it is true only when the system does not generate heat loss. This happens when the output power goes to zero. The efficiency at the maximum power output is quite important in many applications. Research in thermoelectrics has been mostly focused on improving the figure-of-merit (ZT) of the material [1][2][3]. This ZT factor is critical to extract useful power. However, developing the material is not enough to improve the power output of the whole system. Recent work shows that the system efficiency at the maximum power output is linearly dependant on the sum of the heat dissipation on both the hot side and the cold side thermal resistances with the reservoirs [4]. The optimum condition is found only when the thermoelectric device thermal impedance matches the impedance of the system both electrically and thermally by a factor of sqrt(1+ZT). This phenomenon was partially understood and reported in the literature on thermoelectric systems [5][6][7][8]. In the following, we have performed a comprehensive and full optimization based on the generic model with asymmetric thermal resistances with hot and cold reservoirs.

MODEL DEVELOPMENT

The model of the thermoelectric power generation system contains thermal resistance with a hot reservoir, ψ_h, and a cold reservoir, ψ_c as seen as Fig.1. A thermoelectric element (leg) is placed in the middle of two thermal resistances. Heat flux q_h is supplied by the hot reservoir at temperature T_s (fixed). Also, the cold reservoir T_a (fixed) is given. Heat flux q_c flowing into the cold reservoir is reduced from q_h depending on the electrical energy conversion performance. Useful power w is extracted at the external electrical load resistor R_L in the circuit, which is connected to the thermoelectric element.

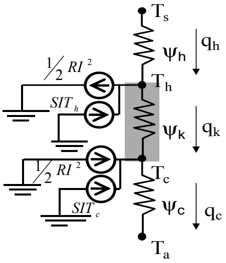

Figure 1. Thermal network: TE element is placed in the dark section between nodes T_h and T_c.

Eqs. 1 and 2 are developed from the energy balance at two node temperatures at the hot side T_h and cold side T_c. In this model, the geometric parameters are considered per unit area.

$$q_h = \frac{\beta}{d}(T_h - T_c) + SIT_h - I^2R/2 \tag{1}$$

$$q_c = \frac{\beta}{d}(T_h - T_c) + SIT_c + I^2R/2 \tag{2}$$

where β is thermal conductivity, d is leg length, S is Seebeck coefficient, I is electrical current, and R is thermoelectric internal resistance. The current I in the circuit is determined by

$$I = \frac{\sigma S}{(1+m)d}(T_h - T_c) \tag{3}$$

where σ is resistivity, m is the resistance ratio of R_L (the load resistor) with respect to R. The output power density w is found by substituting T_s and T_a in T_h and T_c.

$$w = \frac{mZ}{(1+m)^2}\frac{d\beta}{\left(d + \beta\sum\psi\kappa\right)^2}(T_s - T_a)^2 \tag{4}$$

Here, $\Sigma\psi$ is the sum of the thermal resistances at the hot and cold sides. κ is later found as the thermal resistance ratio at the optimum, and its exact expression is

$$\kappa = \left(1 + \frac{Z}{2(1+m)^2}\left((2m+1)T_h + T_c\right)\right)\frac{\psi_h}{\sum\psi} + \left(1 + \frac{Z}{2(1+m)^2}\left(T_h + (2m+1)T_c\right)\right)\frac{\psi_c}{\sum\psi} \tag{5}$$

where Z is the figure-of-merit of thermoelectric material given by

$$Z = \frac{\sigma S^2}{\beta} \tag{6}$$

Optimizing the thermoelectric leg length yields d_{opt}, and the maximum output w_{max},

$$d_{opt} = \beta\kappa A\sum\psi \tag{7}$$