

Development of a 1kW Exhaust Waste Heat Thermoelectric Generator

Lakshmikanth Meda and Martin Romzek
Eberspaecher North America Inc.

Yanliang Zhang
Boise State University

Martin Cleary

ABSTRACT

Although the technology of combustion engines is reasonably well developed, the degree of efficiency is considerably low. Considerable amount of the energy of around 35 % is lost as exhaust waste heat, and up to 30 % is dissipated in the cooling circuits. Due to this, thermal recuperation has a great potential for raising the efficiency of combustion engines. In order to meet the ever-increasing consumer demand for higher fuel economy, and to conform to more stringent governmental regulations, auto manufacturers have increasingly looked at thermoelectric materials as a potential method to recover some of that waste heat and improve the overall efficiency of their vehicle fleets. Seeking new possibilities to make vehicles greener and more efficient, the industry wants to use the waste heat which passes through the exhaust system almost completely unused in the past. The combination of heat exchanger and thermoelectric material integrated into the vehicle environment results in high demands on design, size & dimensioning of the thermoelectric generator system. As a company specializing in the manufacture of exhaust systems for the automotive industry, Eberspächer Exhaust Systems of Americas is uniquely well-positioned to develop and integrate an in-line system for the capture and conversion of thermal energy into electrical energy, and to account for the effects of the heat exchanger on the rest of the exhaust system and engine. In this paper, the stages of the thermal and mechanical design of heat exchanger, material selection, analytical simulations of thermal, contact phenomena, finite element methodology used, physical TEG prototype fabrication and testing stages involved in the development of a 1000 Watt thermoelectric generator (TEG) for a diesel engine of a military tank are explained in detail.

CITATION: Meda, L., Romzek, M., Zhang, Y., and Cleary, M., "Development of a 1kW Exhaust Waste Heat Thermoelectric Generator," *SAE Int. J. Commer. Veh.* 9(1):2016, doi:10.4271/2016-01-1273.

INTRODUCTION

Thermoelectric generators (TEG) are solid-state devices that convert heat directly into electrical energy using a phenomenon called the Seebeck effect. The TE materials used in thermoelectric generators are semiconductors with low thermal conductivity and high electrical conductivity. There are no moving or rotating parts in this device. To generate electrical energy, waste heat is applied to the junction of two electrically opposed materials that are cooled at the opposite end. A TE module consists of multiple leg pairs, each made of n-type and p-type TE materials, which are connected electrically in series and thermally in parallel to form a TE module. The modules are then incorporated into a heat exchange assembly with a hot and cold side forming a thermoelectric generator (TEG). A typical TEG unit consists of a heat exchanger core, thermoelectric modules, a coolant heat exchanger, exhaust gas inlet and outlet diffusers, a bypass pipe (which routes exhaust gas away from the heat exchanger when necessary) and a bypass valve to regulate the flow through the heat exchanger

First, a conceptual TEG system architecture and assembly consisting of TEG modules, hot side heat exchanger, cold side heat exchanger, gas and coolant inlet and outlets is envisioned. The TEG system includes a series of thermoelectric modules (TEMs) sandwiched between the exhaust heat exchangers and cold heat exchangers that effectively transfer the heat into and out of the TEMs in order to establish the maximum temperature gradient. Next, development of 1-D heat & mass transfer analytical tool for a TEG system consisting of hot and cold side heat exchangers and TEG modules is explained. The tool is then used to optimize the fins in the heat exchangers. Finite element method is also used to evaluate the contact pressure distribution adjacent to TEM under bolted assembly loading and under the operating hot conditions. Computational fluid dynamics is also used to optimize the inlet regions of heat exchangers. Once the final optimized fin selection and heat exchanger assembly aspects are decided based on 1-D and FEA simulation results, initially a modular 200 W system representing 1/5th of a complete 1000 W TEG system is fabricated and

tested. After the successful testing of a 200 W TEG system, a final 1kW system is also fabricated and tested. The steps carried out in the above process are described in the following sections.

HEAT EXCHANGER DESIGN

The heat exchanger design utilizes a rectangular, slab like heat exchanger core. Generally, if the exhaust stream is split into two or more streams within the heat exchanger, a greater surface area for the attachment of thermoelectric modules can be created. Extracting thermal energy from the exhaust gas is difficult because of the low gas heat transfer coefficient, typically around 100W/m²-K, at the design condition. The extraction of thermal energy in a heat exchanger can be enhanced by the inclusion of fins in the gas stream, Fins may be plain, offset, triangular or louvered. Fins enhance the overall rate of heat extraction by increasing the heat transfer coefficient and by increasing the overall conducting surface area in contact with the exhaust gas. However, this increase in thermal extraction is bought at the cost of an increased pressure drop across the fins. Within the exhaust, the pressure drop across the TEG unit must be kept within limits; otherwise the overall performance of the engine will be degraded. The literature contains a number of empirical relationships for evaluating the increased heat transfer coefficient and the resulting pressure drop associated with a given fin design. Plain rectangular fins have been chosen for evaluation for inclusion in the TEG in this study as they represent a reasonable compromise between enhanced heat transfer and pressure loss, in addition the small number of design variables and relative ease of manufacture makes them an attractive design choice.

To maximize electrical power output, the design of the TEG was made to get the highest heat transfer between hot gas and the thermoelectric modules, while at the same time keeping exhaust line back-pressure at an acceptable level. Once evaluated for a given fin design, the overall thermal performance of the heat exchanger was calculated using the ϵ -NTU (efficiency, number of transfer units) method. With this method, an overall heat transfer coefficient is derived. This overall value has contributions from the exhaust gas, including the contribution to the increased conduction area from the fins, a contribution from the solid material including TEG modules, graphite layers adjacent to TEG modules between the hot and cold fluids, and the contribution from the coolant heat transfer coefficient. In a conventional heat exchanger, the thermal resistance from the metal interface between the primary and secondary fluids is usually small. With a TEG unit, however, a thermoelectric material is interposed between the hot and the cold surfaces. The thermal conductivity of these materials is very low, typically 1.2 to 3 W/m-K. This is similar to the thermal conductivity of glass or brick and makes a considerable impact on the heat transfer capabilities of the TEG unit.

Consequently, the effect of the additional thermal resistance due to the thermoelectric materials needs to be considered from an early stage in the design. The overall heat transfer of the TEG unit was evaluated for thermoelectric module thicknesses of 5 mm. Some generic Exhaust Heat Exchanger Requirements are 1) Maintain a uniform temperature differential to the TE material at the optimum working TE range, 2) Maximize the overall heat flux through the TE material within the working range, 3) Minimize the exhaust gas-side

pressure drop, 4) Minimize system weight and the incremental thermal inertia of the device, and 5) Providing a means of controlling the heat flux to the TE material and regulating the pressure drop.

TEG MODULE

Figure 1 shows an image of a TEG Module. The TEG modules in this research are made of nanostructured bulk half-Heusler uncouples. Since half-Heusler materials are oxygen-sensitive, the raw module consisting of 28 n- and p- uncouples is sealed in a stainless-steel enclosure in vacuum with two electric feed-throughs. A thin graphite foil is employed between the hot side of the raw module and the enclosure cover to provide a flexible thermal contact in order to relieve thermal stresses under device operation, and the cold side of the module is soldered to the bottom of the enclosure. Refer [2] for more information on the module.

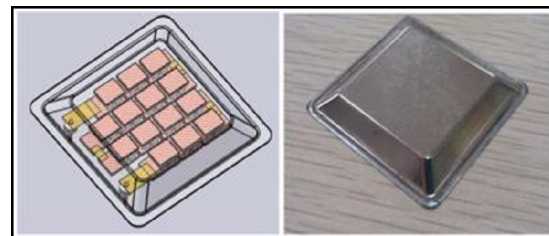


Figure 1. Photographs showing the nanostructured bulk half-Heusler uncouples packaged in a vacuum sealed stainless steel enclosure.

ANALYTICAL THERMAL MODEL FOR THERMOELECTRIC GENERATOR

Heat Exchanger Models

The performance of a heat exchanger can be determined by examining the heat loss and heat gain that takes place between its working fluids.

The actual heat transfer rate can be determined from

$$q = C_c (T_{c,out} - T_{c,in})$$

$$q = C_h (T_{h,in} - T_{h,out})$$

Where

$$C_c = \dot{m}_c \cdot C_{p,c}$$

$$C_h = \dot{m}_h \cdot C_{p,h}$$

The smaller one is defined as Cmin and the larger Cmax

$$q_{\max} = C_{\min} (T_{h,in} - T_{c,in})$$

Where $C_{\min}$ is the smaller of C_h and C_c and $\Delta T_{\max} = T_{h,in} - T_{c,in}$

$$q = \epsilon q_{\max}$$

$$q = \epsilon C_{\min} (T_{h,in} - T_{c,in})$$

Where Cmin is the smaller of Ch and Cc and the effectiveness of heat exchanger can be written as

$$\varepsilon = \frac{q}{q_{\max}} = \frac{\text{actual heat transfer rate}}{\text{maximum possible heat transfer rate}}$$

To determine the effectiveness, ε we involve a dimensionless quantity called **number of transfer units** which is expressed as $NTU = UA/C_{\min}$, where U = overall heat transfer coefficient. The effectiveness of the cross flow heat exchanger is given by

$$\varepsilon = 1 - \exp\left[\frac{1}{C^*}(NTU)^{0.22}\left[\exp\left[-C^*(NTU)^{0.78}\right] - 1\right]\right]$$

Where $C^* = C_{\min}/C_{\max}$

The flow of heat from the hot air to the cold coolant can be represented by Newton's Law of cooling.

$Q = UA(T_h - T_c)$, UA is the reciprocal of resistance.

DITTUS-BOELTER CORRELATION

$$Nu = 0.023 Re^{0.8} Pr^n$$

Here, $n = 0.4$ if the fluid is being heated, that is, if the wall is at a higher temperature than the entering fluid, and $n = 0.3$ if the fluid is being cooled.

Where Prandtl number is $Pr = (C_p \cdot \mu) / K_f$ and Nu and heat transfer coefficient are related by $h = Nu \cdot K_f / D_h$

K_f : Fluid thermal conductivity

c_p : Fluid specific heat at constant pressure

μ : Fluid viscosity

EQUIVALENT THERMAL RESISTANCE MODEL FOR TEG

The TEG system includes a series of thermoelectric modules (TEMs) sandwiched between the exhaust heat exchangers and liquid cold heat exchanger that effectively transfer the heat into and out of the TEMs in order to establish the maximum temperature gradient. TEM's consisting of semiconductor thermoelectric materials are relatively less compliant. The thermal stress between a TEM and the wall of the HEX affects both heat transfer as well as the durability. To reduce the thermal stress in the TEM, compliant pads are used at the interface, although the pads act as a barrier against thermal conduction. Graphite pads are used as compliant pads in this research [1]. Heat transfer from the hot side HEX will occur in the fin through different types of resistances which includes convection and conduction, as presented in Figures 2 & 3. After defining the equations for each resistance, a thermal circuit is built, and an equivalent thermal resistance is calculated. The resistance expressions for hot-side heat exchanger are given below. The other resistances can be obtained similarly from the model presented in Figure 3.

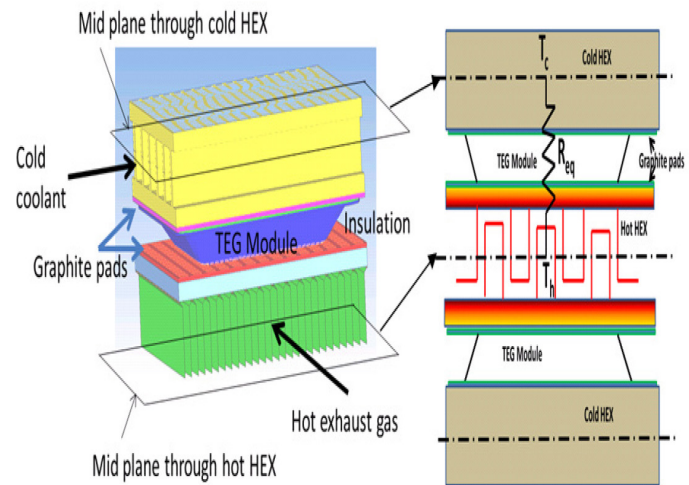


Figure 2. Schematic showing details of hot side HEX and cold side HEX around a TEG module and representation of flow of heat from hot side HEX to cold side HEX by an equivalent thermal resistance (R_{eq}).

$$R1 = 2/(h \cdot N_f \cdot S.L)$$

$$R3 = t/(K_f \cdot N_f \cdot S.L)$$

$$R4 = t_p/(2K_p \cdot N_f \cdot S.L)$$

The efficiency of the fin is given by

$$\varepsilon_f = \tanh(mL_c) / mL_c ; m = \sqrt{h \cdot P / K_f \cdot A_c} ; L_c = P/2$$

Mass Transfer

$$Pr. \text{ Drop through HEX fins core} = (4 \cdot f \cdot L \cdot p \cdot v^2) / (2 \cdot D_h)$$

Where, f is fanning friction factor.

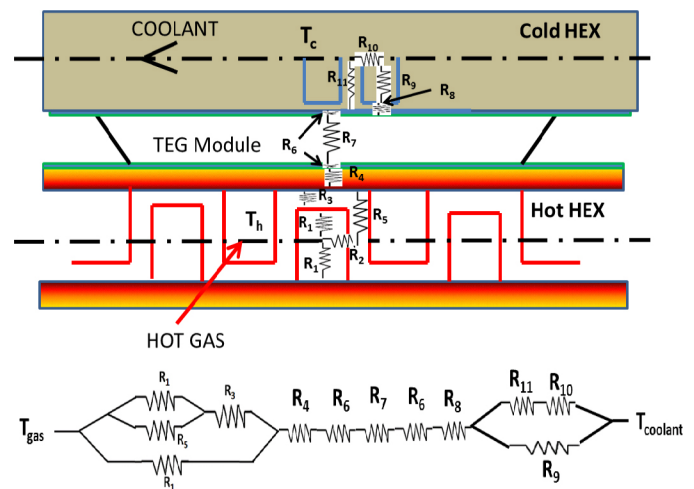


Figure 3. Schematic showing how heat flows from hot side HEX to cold side HEX through a web of parallel and series thermal resistances considering heat flow through convection and conduction