

Thermoelectric Exhaust Heat Recovery for Hybrid Vehicles

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ABSTRACT

Only a part of the energy released from the fuel during combustion is converted to useful work in an engine. The remaining energy is wasted and the exhaust stream is a dominant source of the overall wasted energy. There is renewed interest in the conversion of this energy to increase the fuel efficiency of vehicles. There are several ways this can be accomplished. This work involves the utilization thermoelectric (TE) materials which have the capability to convert heat directly into electricity. A model was developed to study the feasibility of the concept. A Design of Experiment was performed to improve the design on the basis of higher power generation and less TE mass, backpressure, and response time. Results suggest that it is possible to construct a realistic device that can convert part of the wasted exhaust energy into electricity thereby improving the fuel economy of a gas-electric hybrid vehicle.

INTRODUCTION

A recent study [1] estimated that, in a typical internal combustion engine, 21% of the energy release is wasted in exhaust at $\frac{1}{4}$ load and 1500 rpm. This increases to 44% at full load, 4500 rpm. On the average, about one third the energy of the fuel is wasted in the exhaust stream. Methods to utilize this energy are drawing more and more attention in light of demand for increasing vehicle fuel efficiency.

Several methods have been studied in the transportation industry to convert exhaust energy into useful work including electric and mechanical turbo compounding [2], Brayton bottoming cycles [3], and Stirling bottoming cycles [4]. In particular, Rankine cycle waste heat recovery applications have been studied by many investigators in an effort to use exhaust heat to vaporize

a suitable fluid and drive a turbine-generator combination [5-10]. In spite of showing promising system efficiency improvements, the added complexity and weight penalty of these systems makes them less attractive for automotive applications.

On the other hand, thermoelectric power generation has been traditionally used in places where other methods of reliable power generation are not practical. This includes remote geographical locations [11] (e.g., gas pipe lines) and space applications [12]. As a result, there is not an abundance of literature involving automotive applications. Crane et al [13] studied the potential for using waste heat from engine coolant with a thermoelectric device integrated into the radiator. Their modeling results suggested that it is plausible to produce enough power to replace the alternator, and that the penalties associated with increased radiator size and pumping losses are minimal. Thacher et al [14] tested the performance of an exhaust mounted thermoelectric generator in a full size truck with a 5.3L V-8 gasoline engine. The device generated around 180W at 113kph and zero grade. They estimated that this corresponded to a 1-2 percent fuel economy improvement and concluded that to extract more power either a larger unit was necessary or the heat exchanger design needed improvements. Headings et al [15] developed an empirical-based system model and evaluated different systems configuration. From generated power, fuel economy gains were estimated on the basis of alternator work reduction. No backpressure impact was taken into consideration. Yang [16] reports the possibility of generating an average of 350 W on FTP cycles with a conventional full size truck resulting in 3% composite Urban/Highway fuel economy improvement.

This work involved the detailed modeling of a thermal-fluid system in an exhaust thermoelectric generator

device using a 1-D approach. Upon validation of the model, a design optimization was carried out to improve the performance while taking TE mass, backpressure, and thermal response time into consideration. Finally, the transient response under actual drive cycles was evaluated to check the adequacy of the model and to compare to the steady state results.

BASIC THERMOELECTRIC CONCEPTS

In general, a thermoelectric (TE) power generation device works in the same manner as a thermocouple; a principle based on the Seebeck effect [17]. When two dissimilar conductors are joined together at two junctions and the two junctions are kept at two different temperatures, an electric potential is developed that enables current to flow through a resistance. In the case of a thermoelectric module, p-type and n-type semiconductors are used instead of metal conductors.

A figure of merit, Z , is used to define the performance of a thermoelectric material. It is derived from the Seebeck coefficient, electrical conductivity, and thermal conductivity of the material, as shown below.

$$Z = \frac{\alpha^2 \sigma}{\lambda} \quad (1)$$

The product ZT , where $T = (T_h + T_c)/2$, is a non-dimensional number that expresses the figure of merit under a given working temperature. The maximum thermal efficiency is derived as [17].

$$\eta = \left[\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + (T_c/T_h)} \right] \left[\frac{T_h - T_c}{T_h} \right] \quad (2)$$

It is evident that the second term is the Carnot efficiency and a higher value of ZT leads to higher efficiency for a given hot and cold side temperature.

The thermal efficiency of the generator is maximized by choosing an optimum ratio of load resistance to internal resistance [18]. The heat flow to the hot side and heat flow out of the cold side can be written as,

$$Q_h = K\Delta T + \alpha T_h I - \frac{1}{2} I^2 R \quad (3)$$

$$Q_c = K\Delta T + \alpha T_c I + \frac{1}{2} I^2 R \quad (4)$$

In addition to the usual temperature gradient term, two additional current dependent terms play a role in the heat transfer process as seen in Eqn. (3) and (4). To evaluate the current dependent heat flow terms, known as Peltier and Joule terms, the current is calculated as,

$$I = \frac{\alpha \Delta T}{(R + R_L)} \quad (5)$$

The difference of heat going in and coming out is the power produced,

$$P = Q_h - Q_c \quad (6)$$

Power can be also defined as,

$$P = I^2 R_L \quad (7)$$

Thermal efficiency in terms of power is,

$$\eta = \frac{P}{Q_h} \quad (8)$$

DEVICE CONFIGURATION

A thermo-electric generator configured to generate energy from IC engine exhaust flow consists of a number of parallel channels of square cross-section in the direction of exhaust flow. Figure 1 shows the conceptual device configuration used in the study. Thermoelectric modules are placed on the walls of the channels. Diverging and converging cones are placed at the inlet and outlet of the generator to expand and contract the gas with minimum additional backpressure. Coolant flow on the outside of the channel maintains cold side temperature. However, the cold side flow loop was not modeled in this study. Instead, a fixed temperature similar to typical coolant temperature was assumed for the cold side.

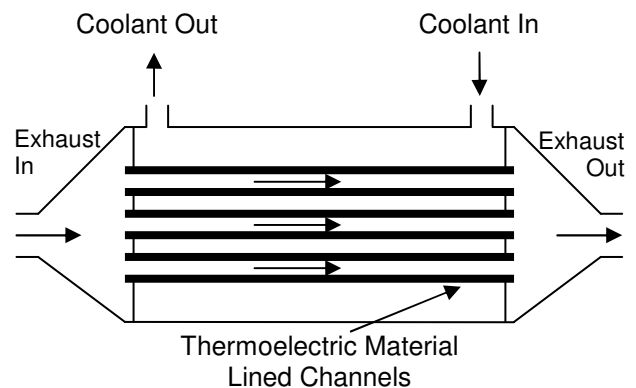


Figure 1: Conceptual design of a direct thermoelectric generator configuration, using a counter-flow heat exchanger design.

The performance of a thermoelectric device for a given gas mass flow rate and temperature is a function of many parameters. The dominant factors are channel width, channel length, channel number, and the thickness of the thermoelectric layer. The design

objective is to produce the maximum power possible with the least amount of TE material (cost constraint) and backpressure (performance constraint). In addition, the system needs to have fast thermal response so that it can reach reasonable generation rate in as little time as possible from start-up.

SYSTEM CONFIGURATIONS

A thermoelectric generator can be configured in direct and indirect system configurations as shown in Figure 2. In a direct configuration, the hot-side of the generator is heated directly by the exhaust gas. In the indirect layout, a heat exchanger was used to heat a suitable working fluid which in turn delivers a hot working fluid to the TE generator. A direct layout is more attractive for automotive applications due to its simplicity at the expense of loss of some degree of control. Only the direct layout configuration was modeled in this study. However, the same methodology can be applied to the study of indirect system configurations.

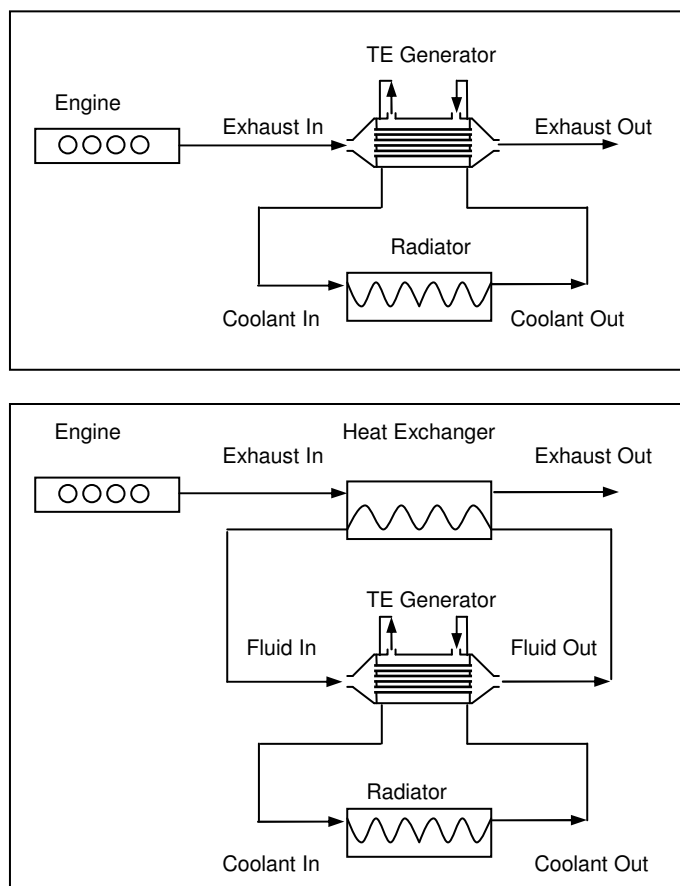


Figure 2: Schematic of a direct (top) and indirect (bottom) thermoelectric generator configuration.

MODEL DEVELOPMENT

A model of a thermoelectric generator was developed using commercial engine cycle simulation software GT-Power. The main advantage of GT-Power is the ability to integrate seamlessly with any engine model. This

allows the evaluation of not only heat recovery but also its impact on backpressure, engine performance, and tailpipe noise at the same time.

A number of assumptions were made to reduce the complexity of the problem:

- No contact resistance between solid to solid interfaces.
- There is no flow path of heat except through the thermoelectric material.
- There is no parasitic loss of heat to the surroundings.
- The Cold junction was kept at a fixed temperature of 100 deg C unless otherwise mentioned.

A lumped mass was used to model the thermoelectric material. This allows the specification of heat source terms necessary to define the Peltier and Joule terms. The source terms were calculated by sensing the TE junction temperatures at every time step. The TE generator was broken up into three segments for better temperature resolution in the lumped masses. In this initial study, the model was run without an engine by specifying only the mass flow and gas temperature at the inlet to the generator. Atmospheric pressure was assumed at the generator outlet. The model is capable of running either in steady or transient mode. Only the transient simulations take the thermal inertia of the system into account.

Thermoelectric material properties were chosen based on publicly available p- and n-type TE data for the temperature range of this study. A lookup-1D object was used to evaluate the TE property as a function of temperature during the model run time. Device walls were made of steel having temperature independent thermal conductivity. Axial heat conduction along the device wall was accounted for, although this was found to be small compared to the magnitude of radial conduction. A schematic diagram of the model used in the GT-Power study is shown in Fig. 3.

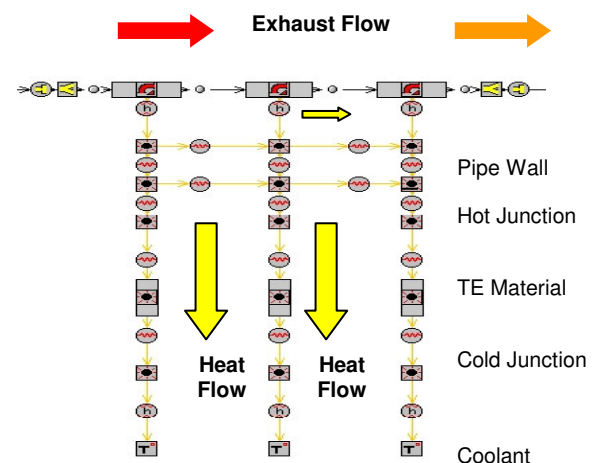


Figure 3: Schematic diagram of the thermoelectric generator model used in GT-Power.

VALIDATION - To validate the model, a single p-n couple having a surface area of 224 mm² was investigated. Mass flow rate and gas temperature was controlled to achieve a desired hot side temperature. The cold side was maintained at a specified temperature. The power and efficiency of the couple was compared against the theoretical value [18] and found to be in good agreement, as shown in Figs. 4 and 5. This confirmed the accuracy of the thermoelectric model as described.

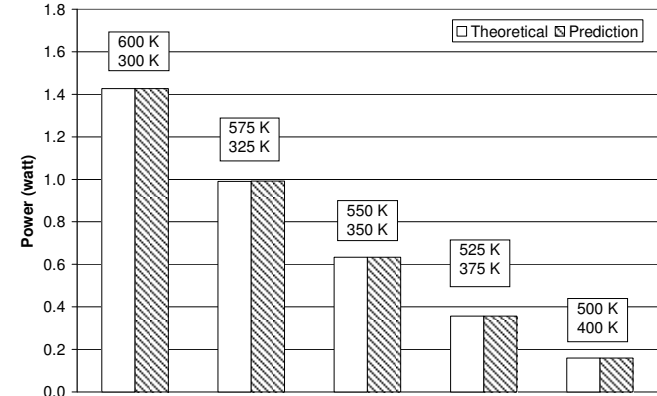


Figure 4: Comparison of prediction versus theoretical output.

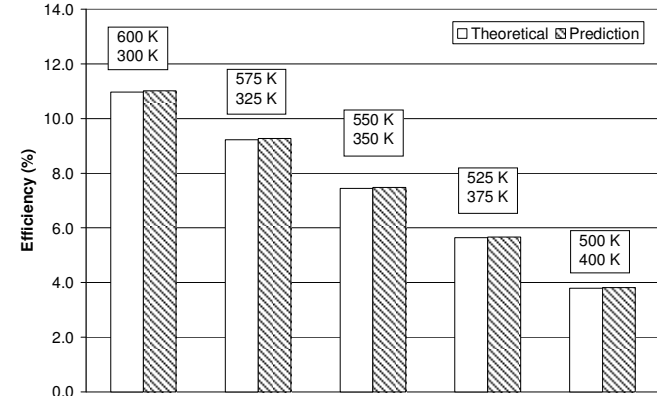


Figure 5: Comparison of prediction versus theoretical thermal efficiency.

RESULTS

DESIGN OF EXPERIMENT - A Design of Experiment (DOE) was conducted within the framework of GT-Power to do a broad sweep of design configurations and identify the most promising ones for automotive applications.

Four design factors were identified as critical for the operation of a TE generator. They are listed below in Table 1 with their range and level.

A time constant parameter, according to the lumped heat capacity method, is defined as [19]

$$\tau = \frac{c\rho V}{hA} \tag{9}$$

Factor	Min Range	Max Range	Level
Channel Length (mm)	100	300	5
Channel Number	5	30	6
Channel Width (mm)	5	10	3
TE Thickness (mm)	2	5	4

Table 1: Factors, ranges and levels used in design of experiment.

This time constant expression was evaluated using the properties of the thermoelectric generator to produce an approximate measure of thermal response of the device. The time constant calculation includes the effect of channel wall and TE material thermal conductivity. The full exhaust system will have a thermal response different than this.

The generated power was derived as a function of TE mass (for cost), pressure drop (for engine performance), and time constant (for quick response). The objective was to maximize power while keeping TE mass, pressure drop, and time constant within acceptable limits.

DISCUSSION

Steady State EPA Highway - A mass flow rate of 56.5 kg/hr and 638 deg C exhaust gas temperature was used in the design of experiment. This is the time averaged value over EPA highway test cycle for 2.5L Escape Hybrid Vehicle with an Atkinson-cycle engine. Although Atkinson engines have lower exhaust energy content because of their inherent higher thermal efficiency, the electricity generated in the thermoelectric module can be used in more than one way in a hybrid vehicle. It can be used to drive the accessory loads, like in a conventional vehicle, or can be used to charge the high voltage battery that is used for traction.

The main effect diagram, Fig. 6, shows the sensitivity of each factor on power generation. It is evident that channel width (W) has the highest slope and was the most sensitive of all the factors.

The results of the DOE study are shown in Fig. 7. Each line in the graph represents the channel number and channel length variables for a fixed channel width, while the TE thickness is variable. In general, as thickness increases (TE mass increases) the power generation reaches a peak and then drops off, as shown in Fig. 7(a).