Power and Efficiency Calculation in Commercial TEG and Application in Wasted Heat Recovery in Automobile

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Abstract

Thermoelectric generators (TEG) make use of the Seebeck effect in semiconductors for the direct conversion of heat into electrical energy, which is of particular interest for high reliability systems or for waste heat recovery. The generator efficiency, η, is determined by comparing the amount of electricity produced (P_{out}) to the total amount of heat induced (Q_{in}). A measuring system and a modeling approach which takes into account the thermal contact resistances have been developed, allowing the characterization of TEG devices under various loads and temperature gradients and thus, to evaluate material properties. These results were used to identify the appropriate positions at the exhaust pipe of a midsize vehicle for the optimum recovery of the wasted heat using a commercial TEG and to establish a set of requirements for an automotive TE waste heat recovery subsystem. Results are presented and discussed.

Introduction

Thermoelectric generators make use of the Seebeck effect in semiconductors for the direct conversion of heat into electrical energy, which is of particular interest for systems of highest reliability or for waste heat recovery [1]. A generator usually consists of several pairs of alternating p- and n-type semiconductor blocks (generator legs), which are arranged thermally parallel and connected electrically in a series circuit. The heat flow, which is partly converted into electrical power, is induced by heating one side of the arrangement while the opposite side is cooled. The conversion efficiency η is defined as the ratio of the generated electrical power P_{TEG} and the heat input into the module Q_H:

$$\eta = \frac{P_{TEG}}{Q_H} \cong \frac{P_{TEG}}{Q_C + P_{TEG}} \quad (1)$$

where Q_C is the heat removed from the cooled side. To accurately determine the efficiency of a generator, the heat induced and the electrical power produced must be carefully measured. Generator efficiencies are often calculated from the measured material properties [2]. This method indirectly yields generator efficiency through the figure of merit, requiring separate measurements of absolute Seebeck, electrical and thermal conductivities of which each is susceptible to a tolerance of errors. More direct measurements of the figure of merit have been demonstrated and are useful to obtain generator efficiency, but the measurement accuracy is limited to testing under small temperature gradients [3-5]. Thermoelectric generator efficiency can also be determined through comparative heat flow, and this method offers a more direct and realistic measurement of a generator's efficiency [6].

The possible use of a device consisting of numerous TEG modules in the wasted heat recovery of an internal combustion (IC) engine can considerably help the world effort for energy savings. Generally, the wasted heat from IC engines is a great percentage of the fuel's energy. In gasoline fuelled IC engines, about 75% of the total energy of the fuel is rejected in the environment [7]. The recovery of a 6% of the exhaust's energy could lead to 10% saving of fuel [8]. Furthermore, the temperatures developed vary from high (about 900 ^{0}C at exhaust manifold) to medium (about 100 ^{0}C in the engine coolant fluid) and thus the efficiency of the thermoelectric elements could be sufficient.

The prevailing modern tendencies in the design of cars lead to the continuous increase of electrically driven elements, while simultaneously the available space for the engine is decreased in order to minimize the aerodynamic coefficient and to maximize the available space for the passengers. The use of a thermoelectric generator device will offload the alternator and thus will reduce its size.

Among the sources of rejected energy that exist in a petrol engine, the initial application of a thermoelectric device can be implemented at the exhaust pipe. The basic reason for this is the high temperatures that prevail there and the big rate of thermal power that goes through. Nevertheless, the application of the device before the catalyst is considered to be undesirable, because it influences the proper operation of the catalyst and the oxygen sensor.

This work focuses on investigating the amount of power that could be recovered from the exhaust pipe of an intermediate size car with the use of conventional thermoelectric elements as well as whether such a solution could be profitable in the automotive industry. However, the methodology used can also be applied for thermoelectric elements with a higher "figure of merit" ZT and respectively higher power output. A measurement method and a theoretical model have been developed, which allow the calculation of gained power and efficiency of a thermoelectric generator device under different electric charges and temperature gradients. With the use of this model we calculated the expected efficiency at different positions of the exhaust pipe and investigated the possible installation places of the device.

TEG Efficiency Calculation

Four basic physical phenomena are associated with the operation of thermoelectric generators (TEG), namely, the Seebeck effect, the Peltier effect, the Thomson effect and Joule effect. Under steady state conditions, the contribution of the four phenomena to energy flow, through a unit volume is expressed as follows:

$$TJ\frac{da}{dx}+\tau J\frac{dT}{dx}-\rho J^2-\frac{d}{dx}\left(\kappa\frac{dT}{dx}\right)=0 \qquad (2)$$

where $\boldsymbol{T}$ is the temperature, $\boldsymbol{J}$ is the electrical current density, $\boldsymbol{\alpha}$ is the Seebeck coefficient, $\boldsymbol{\tau}$ is the Thomson coefficient, $\boldsymbol{\rho}$ is the electrical resistivity and $\boldsymbol{\kappa}$ the thermal conductivity of the material. Neglecting the contribution of Thomson effect, as small, the equation that governs the heat flow at the hot side is:

$$Q_H = K_{TEG}\cdot(T_H-T_C)+S_{TEG}\cdot T_H\cdot I-\tfrac{1}{2}I^2R_{TEG} \qquad (3)$$

where $\boldsymbol{K_{TEG}}$ is the total thermal conductance of the N couples ($K_{TEG}=N(\kappa_n+\kappa_P)G$), $\boldsymbol{S_{TEG}}$ is the total Seebeck coefficient ($S_{TEG}=N(a_n+a_P)$), $\boldsymbol{R_{TEG}}$ is the total resistance ($R_{TEG}=N(\rho_n+\rho_P)/G$) and $\boldsymbol{G}$ is the geometry factor (*G=area/length*). Similarly, the heat flow from the cold junction is

$$Q_C = K_{TEG}\cdot(T_H-T_C)+S_{TEG}\cdot T_C\cdot I+\tfrac{1}{2}I^2R_{TEG} \qquad (4)$$

and thus, the net power produced by the module ($\boldsymbol{P_{TEG}}$) is

$$\begin{aligned}P_{TEG} &= Q_H-Q_C=S_{TEG}\cdot(T_H-T_C)\cdot I-I^2R_{TEG}\\ &=\left[S_{TEG}(T_H-T_C)-IR_{TEG}\right]\cdot I=V_{TEG}I\end{aligned} \qquad (5)$$

and the voltage produced by the module ($\boldsymbol{V_{TEG}}$) is

$$V_{TEG}=S_{TEG}(T_H-T_C)-IR_{TEG} \qquad (6)$$

Therefore, the $\boldsymbol{P_{TEG}}$, $\boldsymbol{Q_H}$, $\boldsymbol{Q_C}$ and $\boldsymbol{\eta}$ can easily be calculated, if the material properties are known. In practice, it is impossible to measure the temperature of both the hot and the cold junction (T_H and T_C), as the p- and n-legs are interconnected by metal (typically Cu) and are thermally in parallel between two ceramic plates. However, it is feasible to measure the temperatures T_1 (hot side area) and T_2 (cold side area) at some distance of the ceramic plates. Assuming that

$$W_{Th(H)}=(W_{th1}+W_{thcnt}+W_{th2}+W_{th3}) \qquad (7)$$

is the total thermal resistance between T_1 and T_H at the hot side, where W_{th1}, W_{th2}, W_{th3} are the thermal conductivity resistances of the copper and ceramic plate layers and W_{thcnt} is the thermal contact resistance between the heater and the ceramic plate (Fig.1), the hot junction temperature T_H is given by the equation

$$T_H=T_1-Q_HW_{Th(H)} \qquad (8)$$

Similarly, the cold junction temperature T_C is given by

$$T_C=T_2+Q_CW_{Th(C)} \qquad (9)$$

where $W_{Th(C)}$ is the total thermal resistance between T_C and T_2.

The set of equations (3)-(6) and (8)-(9) gives

$$Q_H=\frac{B\cdot F-E\cdot C}{B\cdot D-E\cdot A} \quad (10) \qquad Q_C=\frac{C\cdot D-A\cdot F}{B\cdot D-E\cdot A} \quad (11)$$

where

$$A=1+K_{TEG}\cdot W_{Th(H)}+S_{TEG}\cdot I\cdot W_{Th(H)}$$

$$B=K_{TEG}\cdot W_{Th(C)}$$

$$C=K_{TEG}\cdot(T_1-T_2)+S_{TEG}\cdot I\cdot T_1-\tfrac{1}{2}I^2R_{TEG}$$

$$D=K_{TEG}\cdot W_{Th(H)}$$

$$E=1+K_{TEG}\cdot W_{Th(H)}-S_{TEG}\cdot I\cdot W_{Th(C)}$$

$$F=K_{TEG}\cdot(T_1-T_2)+S_{TEG}\cdot I\cdot T_2+\tfrac{1}{2}I^2R_{TEG}$$

and T_H, T_C and P_{TEG} can be easily calculated by the equations (8), (9), (5) respectively.

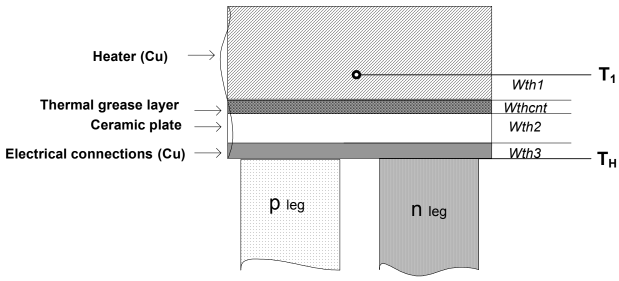

Figure 1: *Thermal resistances between T_1 and T_H*

The calculation of $\boldsymbol{T_H}$ and $\boldsymbol{T_C}$ assumes that the values of $\boldsymbol{\alpha}$, $\boldsymbol{\rho}$ and $\boldsymbol{\kappa}$ are for the $T_{avg}=(T_H+T_C)/2$. As the values of $\boldsymbol{T_H}$ and $\boldsymbol{T_C}$ are still not known, we can approach the result using the values of $\boldsymbol{\alpha}$, $\boldsymbol{\rho}$ and $\boldsymbol{\kappa}$ for $T_{avg1}=(T_1+T_2)/2$ and calculating a couple of values $\boldsymbol{T_{H1}}$ and $\boldsymbol{T_{C1}}$. Using the $T_{avg2}=(T_{H1}+T_{C1})/2$ we can calculate a new pair of values $\boldsymbol{T_{H2}}$ and $\boldsymbol{T_{C2}}$ and so on. The final values for $\boldsymbol{T_H}$ and $\boldsymbol{T_C}$ will result when $(T_{avg(n+1)}-T_{avg(n)}) <$ limit (e.g. 0.1 ^{0}K) [9].

Experimental

A commercial 2.5x2.5 cm Bi_2Te_3 module with N=31 thermocouples (Melcor HT9-3-25) was used. The heater is made from copper and is attached directly to the top of the TEG module. In order to keep a constant cooling temperature, a liquid heat exchanger was used as cooler. All pieces were bonded together with two bolts at a pressure on TEG's surfaces of 4 MPa. In order to reduce the thermal contact resistance, all surfaces lapped at a maximum roughness of about 25 μm and a thin layer of graphite thermal grease (Melcor GRF-159) was used.

For temperature monitoring two K-type thermocouples were mounted, one in a hole of 1mm diameter near the bottom surface of the heater and the other in a thin copper plate on the bottom of the module. An Eliwell EWTR 910 temperature controller controlled the temperature of the heater. A resistance box in combination with a Spectrol 534 potentiometer was used as external load. For the electrical measurements, an Agilent 34401A and a Metrahit multimeters were used as voltmeter and amperometer respectively.

The delivered power $\boldsymbol{P_{TEG}}$ for a module is presented in Fig. 2 along with the calculated curves, where the top curve (dotted) is without any thermal resistance (eq. 3 and 4 and 5). The second curve (dashed) is with the incorporation of thermal resistance (eqs. 10, 11 and 5), including the thermal contact resistance of the grease [10]. A substantial improvement in the description of the P_{TEG} is obtained. Finally, the third curve in Fig. 2 is the calculated curve ($W_{Th(H)}$=0.1486 K/W, $W_{Th(C)}$= 0.1445 K/W), taking into account the thermal resistances of the ceramic plates and the copper electrical contacts as well. Several experiments with different compressions showed that although the pressure increase generally increases the P_{TEG}, negligible improvement with pressures more than 4 MPa can be achieved.

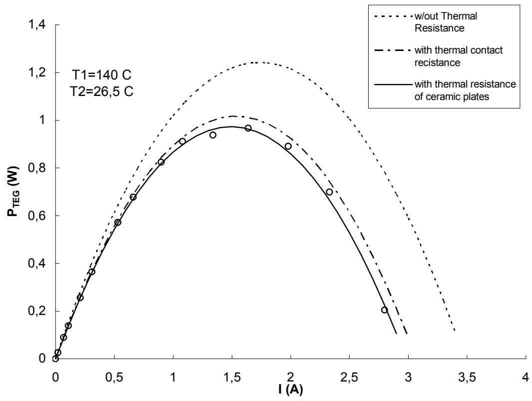

Figure 2: *Experimental and calculated values for Bi_2Te_3 TEG module.*

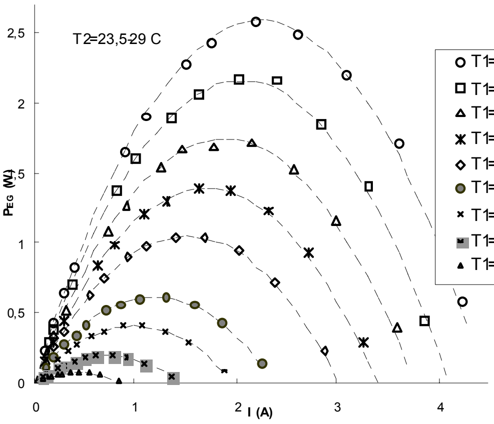

Figure 3: *Measurements and calculated values for Bi_2Te_3 (HT9-3-25) TEG module at various temperatures*

Figure 3 shows the measured and calculated values for the output power P_{TEG}, for various values of hot-side temperature. As can be seen, the maximum power (and accordingly the maximum efficiency) increases with the increase of the hot-side temperature. Curves correspond to the calculated model on thermal resistance, taking the same values ($W_{Th(H)}$ and $W_{Th(C)}$).

Estimation of power gained at different places of exhaust pipe with the use of TEG HT9-3-25.

Figure 4 presents the temperature distribution of the exhaust system components for a 96 KW (BMW 318i, 1995 cm^3) gasoline engine [11]. Assuming that the heat exchanger between exhaust gases and the TEG achieves hot side temperatures T_1 equal to those of the exhaust system components illustrated in Fig.4, the maximum power and efficiency (Fig.5) were calculated for a Melcor HT9-3-25 TEG at different positions of the exhaust pipe after the catalyst. The calculating model used takes into account the thermal contact resistances between heat exchanger surfaces and the TEG elements. As the part load operation is the most typical operational situation for a vehicular gasoline engine, all calculations were made for this condition. The output power and efficiency were calculated for different cold side temperatures T_2 (0 – 120 ^{0}C), in order to have different implementations of the cooling system covered (cooling by ambient air or by the engine coolant, different designs of the heat exchanger etc.). The calculation of the potentially available thermal power at every place of the exhaust pipe shows that, for each combination of engine load and temperature of cold reservoir, the thermal power exceeds the likely maximum required power from the alternator, which can oscillate around 1000 W in modern cars with a lot of electric accessories [12].

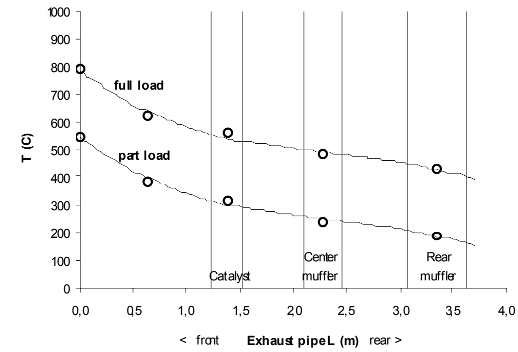

Figure 4: *Temperature distribution at the exhaust system components (after exhaust manifold),(BMW 318i).*

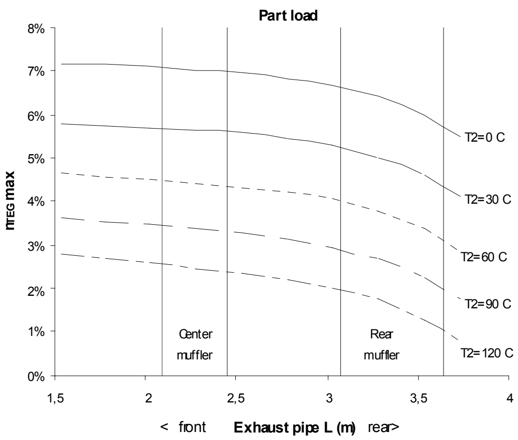

Figure 5: *Maximum efficiency of a TEG HT9-3-25 along the exhaust pipe (after catalyst) for different cold side temperatures T_2.*

The maximum number of TEG modules (of the same type mentioned above) that could be placed for the exploitation of the total thermal power of exhaust gases can be consequently calculated, dividing the potentially available thermal power Q in each point of the exhaust pipe with the heat flow Q_H induced into each module. In this case, the maximum electrical power produced from the device in each place of the exhaust pipe and the corresponding minimal surface required for the heat exchanger, i.e. the sum of all TEG surfaces, are presented in Fig. 6.

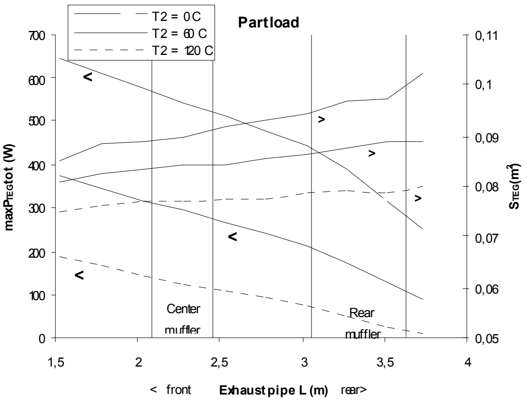

Figure 6: *Maximum TEG device output power and required minimal surface of the heat exchanger along the exhaust pipe (after catalyst), for different cold side temperatures* T_2.

The total gain in fuel consumption that could be economized with the use of a thermoelectric device can be calculated for a 5% reduction in the fuel consumption with current level of technology and for a 20% in future, with the use of new thermoelectric materials (assuming an average consumption of 7.9 lt/100 km and 10.000 km/year). With an estimated cost of the thermoelectric device around 500 €, the depreciation of the device could take place in 3 or 2 years (for the more efficient devices expected in the future) also depending on the future petrol prices.

Conclusions

In this work we developed a model for the evaluation of performance of a thermoelectric generator (TEG). The model, which takes into account the thermal contact resistance and the thermal resistance of the two (top-bottom) ceramic plates of the TEG, has been successfully applied into a commercial TEG. The TEG module was capable to deliver 2.6 W of power when the hot-side temperature was 220 C, which is equivalent of about 5.4 % of efficiency.

The use of thermoelectric materials in vehicular engines for wasted heat recovery, can help considerably in the world need for energy saving and reduction of pollutants. The allocated power and the temperatures that prevail in the exhaust pipe of an intermediate size car are satisfactory enough for the efficient application of a thermoelectric device. The most advisable place appears to be precisely after the catalyst, where high temperatures prevail. The output power and the efficiency of the device depend on the operational situation of the engine and on the effective designing of the heat exchanger. From the results it appears that even with conventional thermoelectric elements, a thermoelectric device with an output power of around 300 W would be feasible, with a corresponding fuel saving of around 5%. Further improvements in the efficiency of the thermoelectric materials, particularly for high temperature operation, are expected to give a revolutionary impulse to their application in the automotive industry.

Acknowledgments

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