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Sensitivity analysis of thermoelectric module performance with respect to geometry

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Many efforts have been done over time to enhance the efficiency of automobiles, but an important fraction (about 80 %) of the energy created by fuel combustion is still wasted through exhaust gas and to the coolant. Extracting useful heat from the waste carried by exhaust and converting it into electricity by using thermoelectric devices seems very attractive. This is true for both conventional cars as well as the more environmentally friendly ones, the electric-hybrid vehicles.

A detailed 1-D model was developed to characterize the operation of a thermoelectric generator. The model allows sensitivity analysis of thermoelectric module performance with respect to geometry, electric and thermal contact resistances, as well as heat source and heat sink qualities (temperature and thermal conductance).

Power density (power generated per kg TE materials) and power output per area are considered more appropriate as criteria of performance, instead of power output and efficiency. TE module performance was analyzed in terms of these criteria. It has been shown that a length exists at which the power output per area has a maximum value, and this maximum is higher for legs with larger cross-sectional area. However, too large cross-sections are not desirables from a thermo-mechanical viewpoint.

The performance of TE module can be significantly increased by limiting electrical as well as thermal contact resistances and by improving the heat transfer coefficient especially on the heat source side. The increase of heat transfer coefficient is obtained with an important pressure drop penalty; the weight of the heat exchanger increases also, both affecting fuel consumption. Therefore, an optimization study based on an economic criterion should be done.

1. Introduction

High fuel prices, resource shortages, climate-change awareness, and international legislation relating to emissions are driving changes that are occurring across many industries. Energy efficiency is becoming an increasingly important issue for many players, including automakers. In automobile industries, efforts to reduce CO_2 emissions have been increasing, particularly in recent years, and accelerated improvements have been shown by refining conventional approaches such as reducing friction and pumping loss, improving combustion concepts and others. However, this

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rate of improvement cannot be sustained by the same approach forever, and these techniques are coming close to their limit. To reduce CO_2 emissions even further, brand new approaches seem to be necessary (Mori et al., 2009); one of them is heat recovery.

Typical thermal efficiencies for automotive internal combustion engines range from 15 to 40% depending on operating conditions as well as engine design. The remaining 60 to 85% of the fuel energy is expelled as waste heat to the environment primarily through the radiator and the exhaust system (Crane et al., 2001). Several methods have been studied in the transportation industry to convert exhaust energy into useful work including electric and mechanical turbo compounding, Brayton and Stirling bottoming cycles and, Rankine cycle. In spite of showing promising system efficiency improvements, the added complexity and weight penalty of these systems makes them less attractive for automotive applications (Hussain et al., 2009).

Due to its simple structure and potential for compactness, thermoelectric conversion could be a good candidate. However, low thermal efficiencies (defined by the ratio of electric work out to heat flux) combined with the relatively high costs of the thermoelectric semiconductor materials have typically kept thermoelectric elements (TE) from being considered as viable technology for automotive applications. Recent advances in materials processing have dropped the cost of mass-producing thermoelectric modules. As a consequence, the efforts aiming to highlight the benefits of thermoelectric generators in waste heat recovering in vehicles have significantly increased (Crane et al., 2001, Fairbanks, 2008, Hussain et al., 2009, Mori et al., 2009). The studies suggest 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 (Crane et al., 2001, Saqr et al., 2008); fuel economy gains and reduction of CO_2 emissions were also estimated (Hussain et al., 2009, Mori et al., 2009).

Usually, the influence of the length of TE having a given cross-section is presented in terms of electric power produced and efficiency, for different operating conditions, considering constant physical properties of materials. These models present different degrees of complexity, since all or only a part of thermal resistances and effects are taken into account (Freunek et al., 2009). Rowe and Min (1996) described a general procedure for optimizing TE module geometry – not related to automotive applications – guided by economic factor (cost/kwh); the module design is a compromise between the requirements for maximum power output and those for maximum conversion efficiency. Rowe and Min (1996) considered that the power output per unit area or – when the cost of input thermal energy is not known – the product of power output per unit area and conversion efficiency.

Mori et al. (2009) considered the influence of electrical output, weight and engine backpressure on fuel economy. Only the influence of TE leg length was taken into account through the mass of the system.

The present work analyzes the performance of TE module in terms of power density (electrical power generated per kg TE materials) and power output per unit area. The influence of TE legs geometry (legs and cross-section area) as well as operating conditions (exhaust gas temperature, type of heat exchanger) is investigated using a 1-D approach. The model includes Joule and Peltier effects, as well as all thermal and electrical resistances. Only Thompson effect is neglected.

2. Theoretical outline

A typical multicouple thermoelectric module is shown schematically in Figure 1: n and p-type semiconductor thermoelements are connected in series by highly conducting metal strips to form a thermocouple. Then, *N* thermocouples are connected electrically in series and sandwiched between thermally conducting but electrically insulating plates. Thermal contact includes ceramic layers, strips and all the interfaces. An imperfect contact between connectors and legs could impact on module's performance.

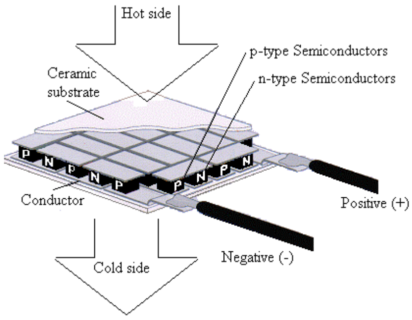

Figure 1. Schematic diagram of a thermoelectric device

The basic physical effects taking place in a thermoelectric generator are thermal conduction and the Seebeck, Peltier, Thomson, and Joule effects. It is assumed that the semiconductor elements are homogenous and thermally and electrically insulated from the surroundings, except at the junction–reservoir contacts. The Thompson effect is also neglected; Ohmic effect in legs is simplified as equally–split heat flux at legs/current collector interface. The basic equations are:

$$U_0 = N \cdot \int_{T_c}^{T_h} S(T)dT \qquad (1)$$

$$I = \frac{U_0}{R_g + R_{load}} \qquad (2)$$

$$P_{out} = U_0{}^2 \frac{R_{load}}{(R_g + R_{load})^2} \qquad (3)$$

$$R_g = R + R_{ch} + R_{cc} \qquad (4)$$

$$Q_h = Q_{p,h} + Q_{n,h} = N \cdot \left((T_h - T_c) \cdot \left[\frac{\lambda_p \cdot A_p}{l_p} + \frac{\lambda_n \cdot A_n}{l_n} \right] + (S_p - S_n) \cdot T_h \cdot I - \frac{I^2}{2} \cdot \left[\frac{\rho_p \cdot A_p}{l_p} + \frac{\rho_n \cdot A_n}{l_n} \right] \right) \qquad (5)$$

$$Q_c = Q_{p,c} + Q_{n,c} = N \cdot \left((T_h - T_c) \cdot [K_p + K_n] + (S_p - S_n) \cdot T_h \cdot I + \frac{I^2}{2} \cdot [R_p + R_n] \right) \qquad (6)$$

$$\eta = \frac{P_{out}}{Q_h} \qquad (7)$$

where U_0 describes the voltage, A and l are the area and length of the legs, T_h and T_c are the temperatures of the hot and cold sides, I is the current passing through, ρ is the electrical resistivity, λ is the thermal conductivity and S is the Seebeck coefficient, R_{load} is the load resistance (considered matched), R_{cc} and R_{ch} are contact resistances at the cold and respectively hot ends, η is the efficiency.

The mathematical model has been solved for a device composed of 12 TE pairs; thus, the assumption of constant temperature on the hot side is valid. TE material physical properties have been considered dependent on temperature.

The influence of hot source has been considered by both its level (exhaust gas temperature) and its conductance. Therefore, the cases of smooth surface and offset strip-fins respectively (Joshi and Webb, 1987) have been analyzed, considering gas mass flow rate corresponding to Steady State EPA Highway (Hussain et al., 2009) and taking into account convection and radiation. As for the heat sink, it was set as coolant at 50 °C having a heat transfer coefficient of 4000 W/m^2K. The legs have equal square cross sections considered to be 3 by 3 and respectively 4.5 by 4.5 mm. The influence of the connectors-leg contact has been highlighted assuming (a) perfect contact and respectively (b) thermal resistance equivalent to 30 µm air. The electrical contact resistance has been considered to be as high as 15 mΩ/pair (for 3 by 3 legs) and respectively 6.72 mΩ/pair (for 4.5 by 4.5 mm legs).

3. Results and discussion

As already stated, power output and conversion efficiency are the parameters generally looked at, and an appropriate thermo-element length for power generation is considered to be a compromise between the requirements for maximum power output and maximum conversion efficiency (Rowe and Min, 1996). However, in waste heat utilisation, low efficiency should not be the most critical drawback, since there is no cost associated with the thermal input. This is why power density and power output per area are considered more appropriate to characterise the performances of TE module.

The influence of the difference of temperature between heat source and heat sink has already been shown to have a big impact on TE performance (Freunek et al., 2009, Mori et al., 2009), so only the results obtained at low exhaust gas temperature (300 °C) will be shown. Due to significantly higher heat transfer coefficients when using the extended surface, both power density and power output per area are few times higher in this case compared with smooth surface. The improvement factor (extended/smooth surface) of these criteria is about 15 for short legs and decreases whit the increase of leg length up to about 3 (not shown).

Cross-section area of TE has a big impact on the power output and, for the studied cases, almost no or very small influence on the efficiency (Figure 2).

Analyzing only the output power could lead to the conclusion that legs having bigger cross-section would be a good choice. However, when looking at power density and power per area, one can observe that short legs with smaller cross-section give higher power density and comparable power per area as legs having bigger cross-section. Long legs give slightly lower power density but improved power per area which is maximal for a certain length (Figure 3 right).

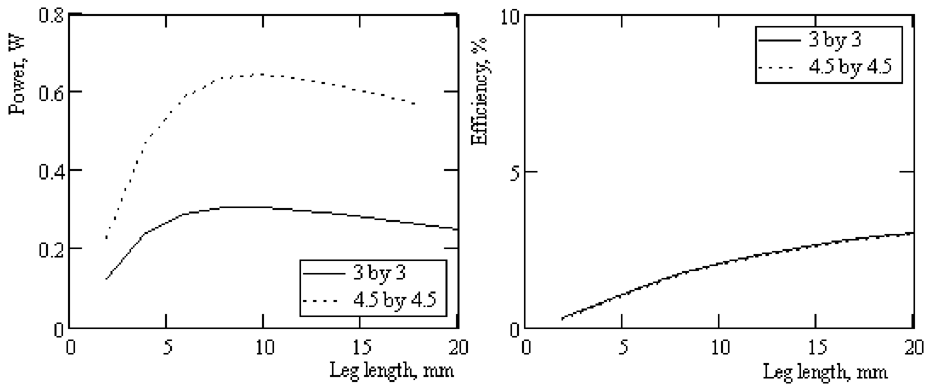

Figure 2: Influence of cross-section and leg length on power output and efficiency (extended surface, gas temperature 300 °C; no thermal contact resistance)

Thus, the choice of geometry will probably be driven by the maximum power output per area. Thermal contact resistance has a big impact on the performance; for example, for 4.5 by 4.5 legs, the maximum power output per area decreases by about 30 % because of it (Figure 3 left).

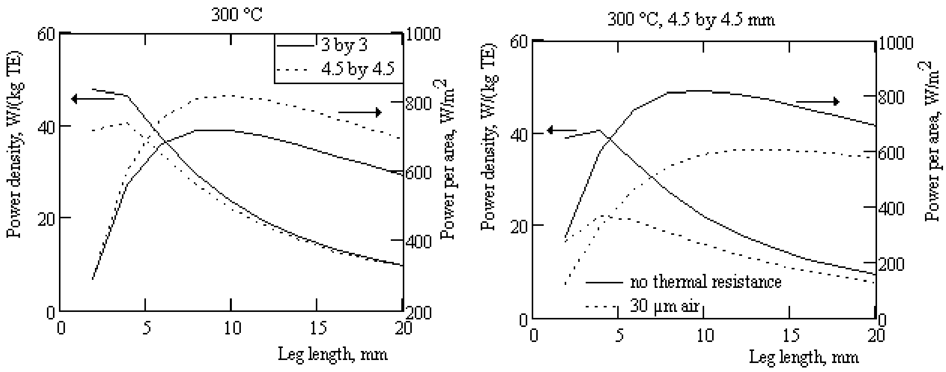

Figure 3. Right: Influence of cross-section and leg length on power density and power output per area (extended surface, gas temperature 300 °C; no thermal contact resistance); left: Influence of thermal contact resistance on power density and power output per area (extended surface, gas temperature 300 °C; legs of 4.5 by 4.5 mm)

4. Conclusions

A detailed 1-D model was developed to characterize the operation of a thermoelectric generator. The model allows sensitivity analysis of thermoelectric module performance with respect to geometry, electric and thermal contact resistances, as well as heat source and heat sink qualities (temperature and thermal conductance).

For a given cross-section area, the output power depends on two opposite effects: (i) shorter legs give smaller electrical resistance, (ii) longer legs ensure a higher temperature difference between the ends. Therefore, there exists an optimum leg length corresponding to a certain cross-section and to a certain TE application such as gas temperatures, and the geometry of hot surface.

Power density (power generated per kg TE materials) is suggested to be used together with power output per area as criteria of performance, instead of power output and efficiency, and TE module performance was analyzed in terms of these criteria.

Regarding the leg cross-section area, the larger it is, the more power it can generate per unit area, as long as the overall surface is not decreasing the available thermal gradient to an unacceptable value; too large cross-sections are not desirables from thermo-mechanical viewpoint neither.

The performance of TE module can be dramatically increased by decreasing electrical as well as thermal contact resistances and by improving the heat transfer coefficient especially on the heat source side. The increase of heat transfer coefficient is obtained with an important pressure drop penalty; the weight of the heat exchanger increases also, both affecting fuel consumption. Therefore, an optimization study based on an economic criterion should be done.

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