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EFFECT OF AIR COOLING ON THE EFFICIENCY OF SECTIONAL THERMOELECTRIC GENERATOR IN A CAR WITH A PETROL ENGINE

The paper is concerned with a physical model of sectional thermoelectric generator (TEG) for a petrol engine with a system of heat removal from TEG comprising an air-to-liquid heat exchanger and an electric fan. Computer simulation of TEG operation for a 70 kW petrol engine is performed. The optimal hot temperatures of the generator sections and the optimal fan powers whereby maximum real TEG efficiency is attained with regard to the costs of power supply to the fan for ambient temperatures in the range of –40…+50^{o}C are found. A comparison of sectional generator efficiency to the previously obtained values for one-section TEG is made. It is shown that a real efficiency of sectional TEG with a heat removal system is 1.2 – 1.4 times higher than that of one-section TEG. It is shown that the costs of power supply to heat removal system can reach 20…30% of TEG power.

Keywords: heat recovery, thermoelectric generator, internal combustion engines.

Introduction

The interest in using thermoelectric generators (TEG) for the recovery of exhaust heat of internal combustions engines remains unchanged. Analysis of international thermoelectric conference proceedings shows that the number of papers dealing with automotive applications of thermoelectricity is constantly growing [1] with creation of special sessions covering this subject [2]. This clearly demonstrates the invariable urgency of this line. The purpose of using TEG in a car is fuel saving due to utilization of engine exhaust heat for electric energy generation.

The presence of thermoelectric generator in a car creates additional problems related to TEG operation. One of them is to assure efficient heat removal from thermoelectric generator. Optimization of the costs of heat removal from one-section thermoelectric generator for cars with different engine types was performed in [3, 4]. Optimization of three-section TEG with a heat removal system for diesel engine was done in [5]. Investigations show that the costs of heat removal from TEG can reach 15-25% of electric energy produced by TEG with the optimal design of heat removal system. Of current interest is further study with a view to establish similar laws for sectional TEG in petrol engines, because as far as is known [4, 5], the use of sectional TEG for petrol engines provides for higher efficiency of waste heat recovery.

The purpose of this work is to estimate the efficiency of using sectional TEG in a car with petrol engine with regard to the costs of energy for heat removal from TEG.

Physical model

The work of sectional thermoelectric generator as part of a car can be represented by a schematic shown in Fig. 1. Exhaust gas of thermal power Q_{in} and temperature T_{in} from engine 1 comes to hot heat exchanger 3 of sectional thermoelectric generator 2. Pat of the heat from the hot heat exchanger is transferred to thermopiles 4 which convert it to electric energy. TEG produces total electric power W_{TEG} at efficiency η_{TEG} . Part of this electric power W_{cool} is spent on the work of cooling system 6 which removes thermal power Q_{TEG} from the cold heat exchanger 5. The temperature of the cold heat exchanger is considered to be fixed.

Such a physical model and its mathematical description are detailed in [5]. The distinctive feature of the model in the present paper is that the temperature of exhaust gases in petrol engines is higher (~800ºC). This necessitates the use in TEG sections of different thermoelectric materials optimized for the necessary temperature range.

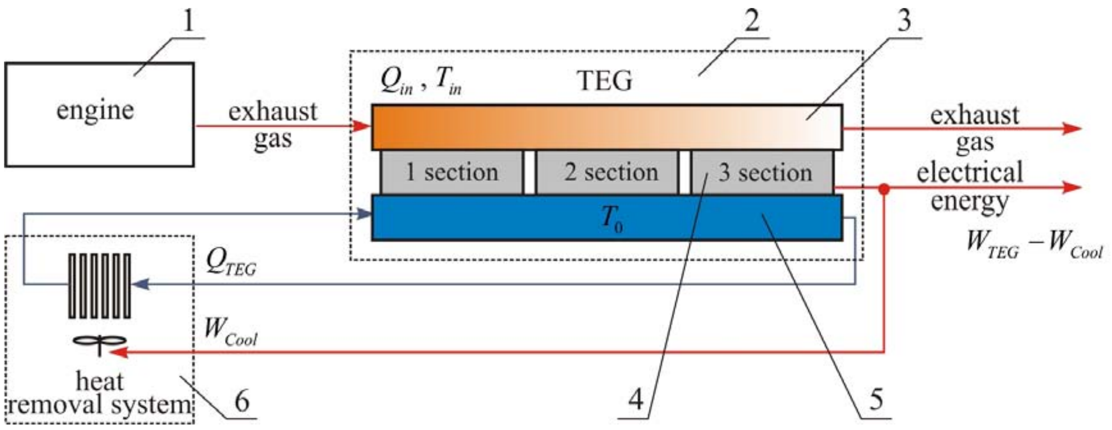

Fig. 1. A model of TEG operation in a car with regard to the costs of electric energy on heat removal from thermal generator. 1 – engine; 2 – sectional TEG; 3 – hot heat exchanger; 4 – thermopiles; 5 – cold heat exchanger, 6 – heat removal system.

As before, maximum efficiency of sectional thermoelectric generator was calculated according to method [5] by means of computer simulation [6] on a two-dimensional finite-element mesh. In short, it is as follows. At first, the hot temperatures of sections are optimized by varying thermal resistances of sections for achieving maximum TEG efficiency:

$$\eta_{TEG} = \frac{W_{TEG}}{Q_H^{in}}. \quad (1)$$

For the optimization of heat removal system a function of the efficiency of air-to-liquid heat exchanger is introduced as below

$$Q_{cool} = f(W_{cool}, T_L, T_A) \quad (2)$$

where Q_{cool} is thermal power of heat removal system, W_{cool} is electric supply power of heat removal system, T_L is liquid temperature, T_A is air temperature. This function is used for calculation of optimal supply power of heat removal system.

The effective efficiency of TEG is found from the expression:

$$\eta_{ef} = (W_{TEG} - W_{cool}) / Q_{in}. \quad (3)$$

Example of parameters calculation for TEG with cooling system

As an example, we shall perform optimization of sectional TEG with cooling system for a stock 70 kW petrol engine UMZ-3318 with the exhaust gas temperature ~790°C. For the calculation of the efficiency and power of such TEG the *n-PbTe* and *p-TAGS* thermoelectric materials were selected that are among the best in the figure of merit in the high-temperature range. Materials based on *Bi-Te* were selected for lower-temperature sections [7]. The *ZT* value of modules made of such materials is given in Fig. 2 [7].

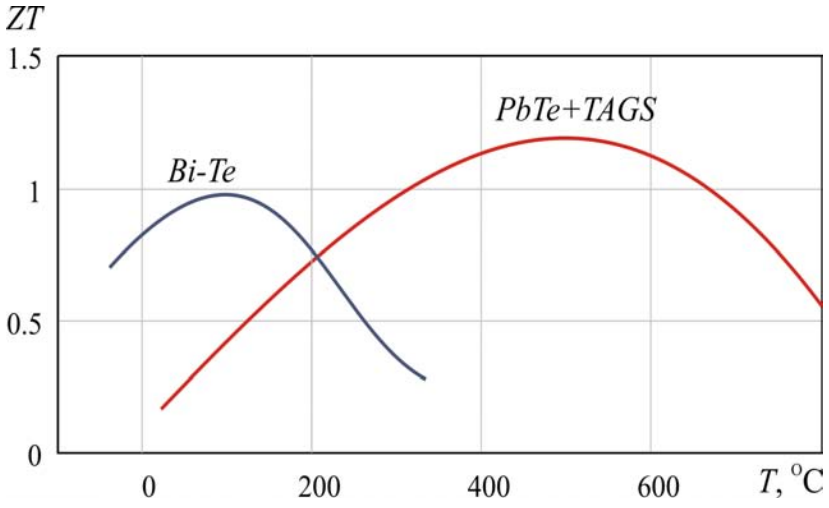

Fig. 2. Temperature dependence of ZT of modules made of materials based on Bi-Te and PbTe + TAGS.

TEG hot side temperature optimization. In the beginning, calculation and optimization of the hot temperatures of TEG sections took place according to procedure [5]. Fig. 3 shows an example of a two-dimensional temperature field in TEG sections calculated by computer simulation. Fig. 4 shows the values of the optimal hot temperatures of sections versus their cold temperature.

As is evident from Fig. 4, the optimal hot temperature of the third section does not rise above 280 ºC. Therefore, for this section it is more reasonable to use thermopiles of *Bi-Te* materials (Fig. 2). The temperatures of the first two sections are sufficiently high for using thermopiles of *n-PbTe* and *p-TAGS* materials in them. Further calculations will be performed for precisely this model.

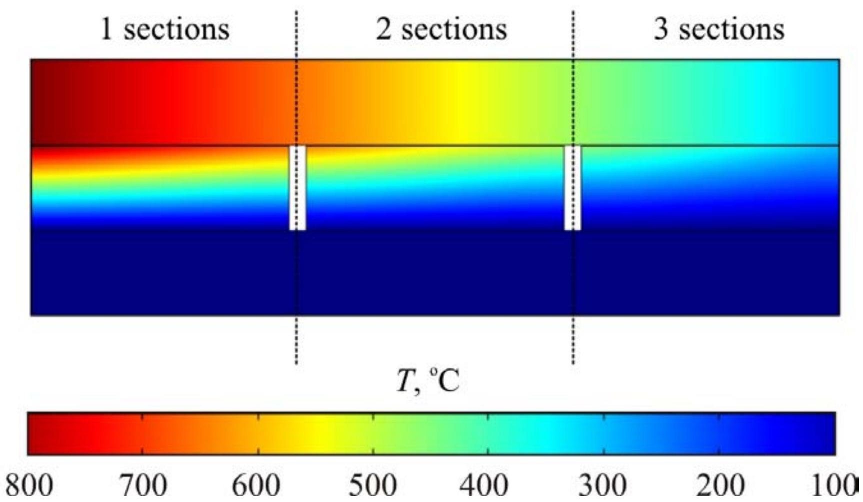

Fig. 3. Temperature distribution in TEG sections.

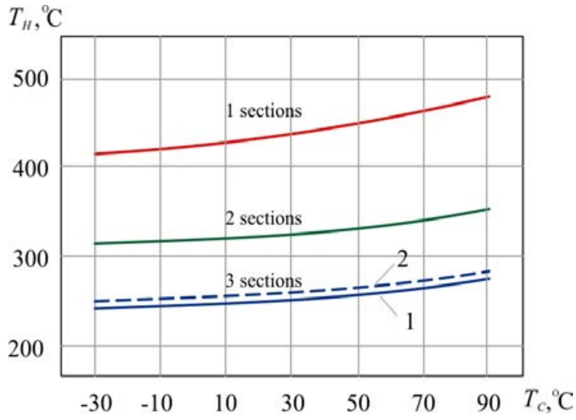

Fig. 4. The optimal hot temperature of TEG sections versus their cold temperature.
1 – for Bi-Te modules, 2 – for n-PbTe and p-TAGS modules.

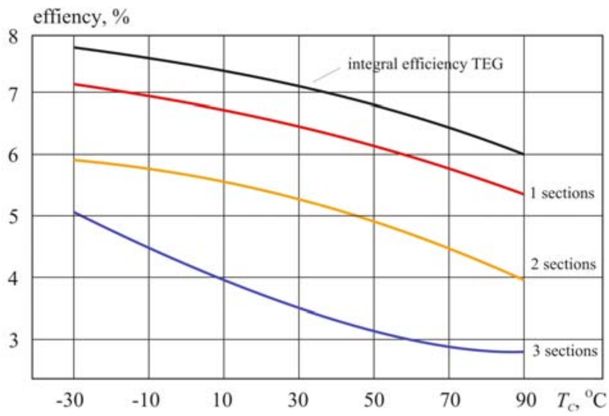

Fig. 5. The efficiency of sections and the integral TEG efficiency
versus the cold side temperature of TEG.

Heat removal system optimization. The optimal costs of heat removal from the TEG sections were calculated according to procedure [3, 4]. Characteristics of air-to-liquid heat exchanger necessary for the calculations were taken from [3]. Fig. 6 gives the value of thermal power to be removed from TEG versus the cold temperature of TEG.

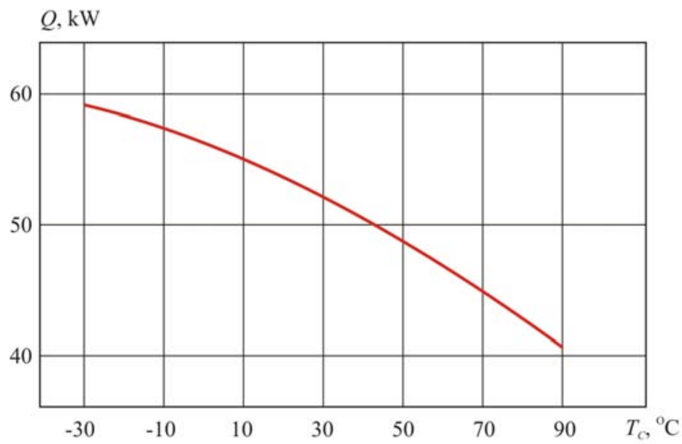

Fig. 6. Thermal power to be removed from TEG versus the cold temperature of TEG.

Fig. 7 shows the results of "TEG-cooling system" optimization for different ambient temperatures. The optimal power values of cooling system fan are presented here. They make ~20%...30% of thermal generator power. Fig. 8 shows the electric power of TEG versus ambient temperature with regard to the costs of heat removal.

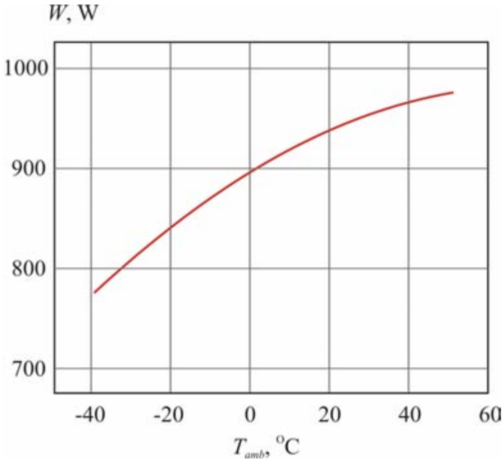

Fig. 7. The optimal electric power of TEG cooling system versus the ambient temperature.

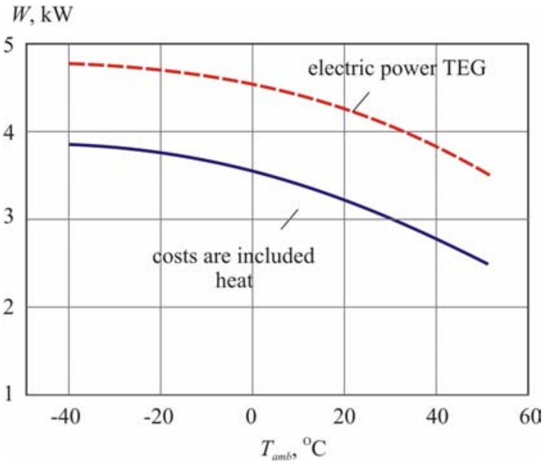

Fig. 8. The electric power of TEG versus the ambient temperature.

Fig. 9 compares the efficiency of one-section TEG [5] and three-section TEG analyzed in the present paper, as well as the efficiency of TEG for a diesel engine analyzed in [3, 5].

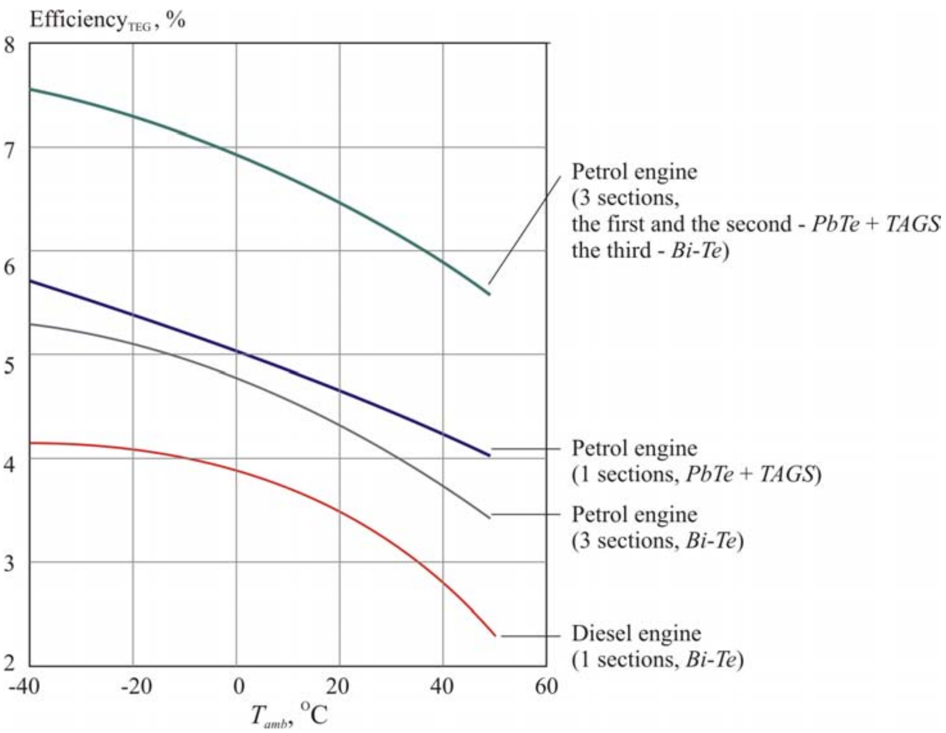

Fig. 9. TEG efficiency versus the ambient temperature.

It is seen that the use of generator sections, under otherwise equal conditions, yields better efficiency values. The use of sections assures 1.2 -1.3 times higher efficiency of TEG. As compared to TEG for a diesel engine, TEG for a petrol engine yields better figures both in efficiency and its stability versus the ambient temperature.

Conclusions

1. By means of computer simulation a physical model of three-section thermoelectric generator for a car with a petrol engine has been analyzed. Computer simulation efficiency has been demonstrated on a specific generator version for a car with a 70 kW petrol engine.
2. The optimal hot temperatures of sections have been obtained as a function of the cold side temperature of TEG in the range of –30…+90 ºC. It has been established that with a rise in the cold side temperature of TEG, the optimal hot temperatures are also displaced towards the range of higher values.
3. Optimization of heat removal system has been performed. The optimal costs of electric energy for heat removal have been found. It has been established that these costs increase from 770 W to 940 W with a rise in ambient temperature from –40 ºC to +50 ºC.
4. The power of TEG as a function of ambient temperature has been determined. It has been established that the highest power value (~4.7 kW) is achieved at $T_{amb} = -40$ ºC and reduced to 3.5 kW at $T_{amb} = +50$ ºC. Part of this energy is spent on assuring heat removal from TEG. With regard to these expenditures, the generator power at $T_{amb} = -40$ ºC is 3.8 kW and reduced to 2.6 kW at $T_{amb} = +50$ ºC.
5. A comparison of the efficiency of one-section and three-section generators demonstrates efficiency increase with the use of three sections from 5.8% to 7.5% at $T_{amb} = -40$ ºC. The efficiency of three-section generator remains higher at elevated ambient temperatures as well. At $T_{amb} = +50$ ºC the efficiency of three-section TEG is 5.63%, whereas the efficiency of one-section TEG is as low as 4%. In general, the investigations performed demonstrate the advantages of three-section TEG in electric power and efficiency by a factor of 1.2…1.4.
6. A system of heat removal from three-section TEG consumes a considerable amount of electric energy. These costs can make 20…30% of the total TEG power.
7. In the range of ambient temperatures –40…+60 ºC the efficiency of TEG for a petrol engine is reduced by ~14%. At the same time, the efficiency of TEG for a diesel engine is reduced by 45%. This testifies to the advisability of using TEG for diesel engines only at reduced ambient temperatures. Since the efficiency of TEG for a petrol engine is less dependent on the ambient temperature, it can be used in a wide range of above temperatures.

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