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

The paper is concerned with a physical model of sectional thermoelectric generator (TEG) for a diesel engine with a system of heat removal from TEG comprising an air-to-liquid heat exchanger and an electric fan. A mathematical description of the model is presented. A computer model of sectional TEG is developed. Computer simulation for a 75 kW disel engine is performed. The optimal hot temperatures of the generator sections and the optimal fan powers whereby maximum net power is attained and, accordingly, maximum real efficiency of TEG with regard to expenditures on the fan supply for ambient temperatures in the range of $-40\ldots+50^{O}C$ *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.*

Key words: heat recovery, thermoelectric generator, internal combustion engines.

Introduction

The use of waste heat from internal combustion engines is a relevant practical application of thermoelectricity. Its purpose is fuel saving due to the use of engine exhaust heat for electric energy generation [1, 2]. It is known that the presence of a thermoelectric generator in a car has a considerable impact on its operation. One of the negative factors reducing TEG efficiency are the expenditures related to the necessity of heat removal from a thermoelectric generator. A detailed estimate of expenditures on heat removal from one-section thermoelectric generator for cars with different engine types is given in [3, 4]. It is shown that expenditures on heat removal from one-section TEG by heat-exchangers with electric fans can reach 15-25% of the electric energy produced by TEG. It is also established that the efficiency of heat removal from TEG in a car has optimal values that depend on the supply power of heat removal system and ambient air temperature. It is important to proceed with investigations in order to establish similar laws for sectional TEG, because, as is known [1, 2], the use of sectional TEG assures more efficient exhaust heat recovery.

The purpose of this work is to develop computer simulation procedure for sectional thermoelectric generator for a car with a diesel engine and liquid-air cooling and to verify its efficiency for a concrete case of engine and thermal generator.

Physical model of sectional thermoelectric generator for a car

A detailed analysis of a physical model of a car with one-section TEG with regard to heat removal from the TEG and its mathematical description is given in [3]. The specific feature of a model in the present paper is that the TEG comprises 3 sections. As is shown in [6], sectioning yields higher TEG efficiency, however, the use of a larger number of sections is not reasonable. So, let us dwell in detail on TEG model.

The maximum efficiency of sectional thermoelectric generator was calculated according to method [1, 7]. Let us consider a TEG consisting of 3 sections connected in series relative to hot gas flow and cold heat carrier (Fig. 1).

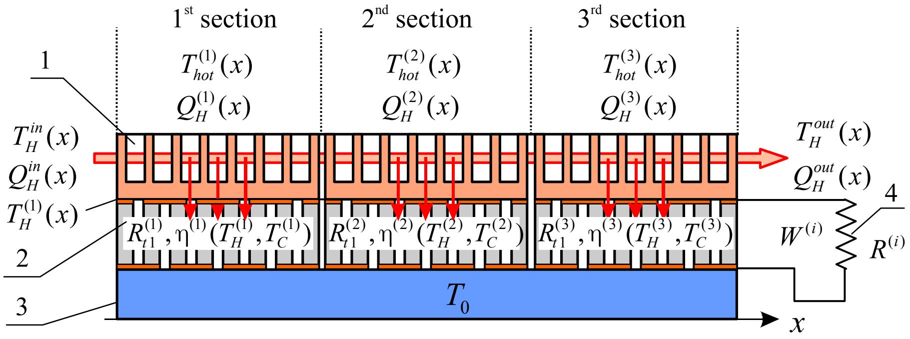

Fig. 1. A physical model of a sectional thermoelectric generator:
1 – hot heat exchanger; 2 – thermopiles; 3 – cold heat exchanger;
4 – matched electric load of a section.

Each TEG section consists of a hot heat exchanger (1), a thermopile (2) with thermal resistance $R_{t1}^{(i)}$ and efficiency $\eta(T_H, T_0)$; a cold heat exchanger (3) with temperature T_0. The thermopiles of each section are loaded on matched electric load $R^{(i)}$ (4). The inlet hot gas flow has temperature T_H^{in} and thermal power Q_H^{in}. The hot gas gives part of heat $Q_H^{(i)}(x)$ at temperature $T_{hot}^{(i)}(x)$ to the hot heat-exchanger. At TEG outlet, the gas flow has temperature T_H^{out} and thermal power Q_H^{out}. Heat from the hot heat-exchanger is transferred to the thermopile heating its hot side to temperature $T_H^{(i)}(x)$. The cold side of thermopiles is maintained at temperature T_0. For the calculations of maximum possible TEG power the thermal expenditures will be ignored.

Mathematical and computer description of the model

For thermoelectric generator optimization it is necessary to find the temperature and heat flow distributions in the thermopiles of each section. Such a calculation for the presented model is possible only with the use of computer simulation.

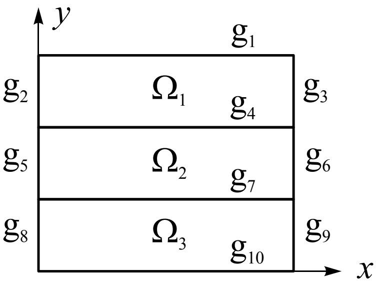

Fig. 2. Computer representation of the areas and boundaries of TEG section.

Let us consider one of generator sections and conventionally divide it into 3 areas $\Omega_1 - \Omega_3$ with the boundaries $g_1 - g_{10}$ (Fig. 2). The area Ω_1 is the hot heat exchanger with a heat carrier, Ω_2 is the thermopile, Ω_3 - the hot and cold heat exchangers.

In the area Ω_1 there is mass transfer of the hot heat carrier. For this area the thermal conductivity equation will be given by

$$-\nabla\left(\kappa_H(T)\nabla T\right) = -\rho_H(T)C_H(T)\vec{v}\nabla T\,, \qquad (1)$$

where ρ_H is gas density, C_H is gas heat capacity, κ_H is gas thermal conductivity, v_H is gas velocity. The boundary conditions for the area Ω_1 take into account the continuity of gas flow within a section and between the sections, heat flow through heat exchangers.

In the area Ω_2 there is the Joule heat release in the thermopile. For the area Ω_2 the thermal conductivity equation is given by

$$-\nabla\left(\kappa_{TE}(T)\nabla T\right)=Q_J \tag{2}$$

where κ_{TE} is the effective thermal conductivity of the thermopile, Q_J is the Joule heat released in the bulk of the thermopile.

The boundary conditions for the area Ω_2 take into account the interaction between the thermopile and the heat exchangers.

The area Ω_3 in this TEG model is considered to be thermostated with temperature T_0.

Mathematically, a set of the boundary conditions is expressed as follows:

g1: $$q_1^{(i)}(x)=0\,, \tag{3}$$

g2, g3: $$Q_H^{in(1)}=Q_H^{in},\ Q_H^{in(i+1)}=Q_H^{out(i)},\ Q_H^{out(N)}=Q_H^{out}\,, \tag{4}$$

g4: $$Q_H^{(i)}(x)=\left(T_H^{(i)}(x)-T^{(i)}(x)\right)/R_{t1}^{(i)} \tag{5}$$

g5, g6: $$q_4^{(i)}(y)=0\,, \tag{6}$$

g7: $$Q_C^{(i)}(x)=\left(T_C^{(i)}(x)-T^{(i)}(x)\right)/R_{t2}\,,$$

$$T(x)=T_0 \tag{7}$$

Ω_3, g8, g9, g10: $$T(x,y)=T_0 \tag{8}$$

A set of equations (1)-(2) with the boundary conditions (3-8) allows to find the temperature field $T(x,y)$ in the TEG and to determine the distribution of temperatures $T_H^{(i)}(x)$ across the hot sides of the thermopiles in the sections.

Then the power of each section can be found from the following expression:

$$W^{(i)}=\int Q_H^{(i)}(x)\eta(T_H^{(i)}(x),\,T_C^{(i)}(x))dx\,. \tag{9}$$

Total generator power

$$W_{TEG}=W^{(1)}+W^{(2)}+W^{(3)}\,. \tag{10}$$

The efficiency of thermoelectric generator

$$\eta_{TEG}=\frac{W_{TEG}}{Q_H^{in}}\,. \tag{11}$$

To calculate the electric power of TEG with regard to provision of heat removal system operation, one should know the efficiency of air-to-liquid heat exchanger

$$Q_{cool}=f(W_{cool},T_L,T_A) \tag{12}$$

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 dependence was obtained from the experimental investigations of the heat exchanger [3].

The effective efficiency of TEG is introduced by the expression:

$$\eta_{ef}=(W_{TEG}-W_{cool})/Q_{in}\,. \tag{13}$$

The system of equations (1)-(2) with the boundary conditions (3)-(8) was solved by finite element method [6] on a 2-dimensional mesh.

Fig. 3 gives an example of computer-simulated 2-dimensional temperature field in TEG sections.

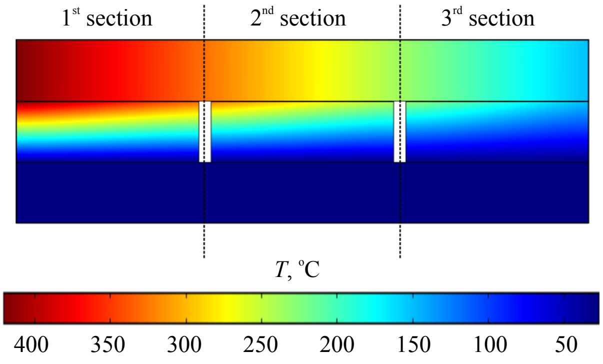

Fig. 3. Temperature distribution in TEG sections.

Further TEG optimization consists in finding the optimal hot temperatures by varying thermal resistances of sections to reach maximum integral efficiency of TEG.

Example of TEG parameters calculation

As an example, we shall calculate the basic parameters of sectional TEG for a 75 kW diesel engine with the exhaust gas temperature 420°C.

For the efficiency and power calculation, the thermoelectric materials based on *Bi-Te*, whose figure of merit is among the best in the operating temperature range of TEG diesel engines, were selected [6]. The characteristics of air-to-liquid heat exchanger necessary for calculations were taken from [3].

TEG hot side temperature optimization. In the beginning, optimization for the hot temperatures of TEG sections took place according to procedure [2]. Fig. 4 shows an example of such optimization for the third TEG section. It is seen that there exists optimal TEG efficiency that depends on the hot and cold temperatures. Fig. 5 shows the values of the optimal hot temperatures of sections versus their cold temperature.

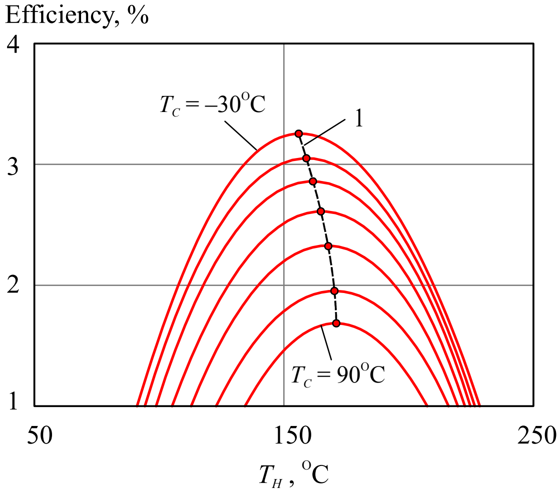

Fig. 4. The efficiency of 3rd TEG section versus section hot temperature. T_C varies from –30°C to +90°C. 1 are optimal hot temperatures.

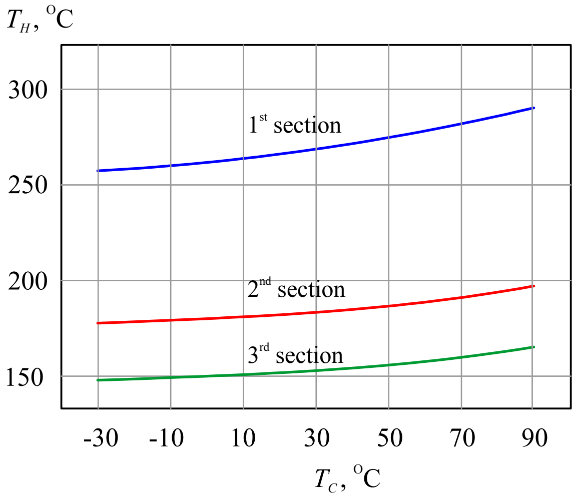

Fig. 5. Optimal hot temperature of TEG sections versus their cold temperature.

Heat removal system optimization. Calculation of the optimal expenditures on heat removal from TEG sections took place according to procedure [3, 4]. Fig. 4 shows the value of thermal power to be removed from TEG versus the cold temperature of TEG.

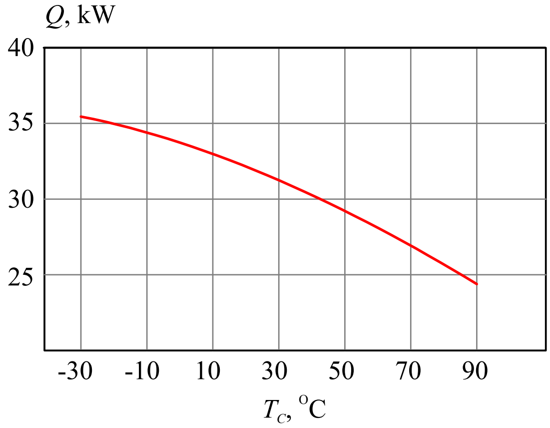

Fig. 6. Thermal power to be removed from TEG versus the cold temperature of TEG.

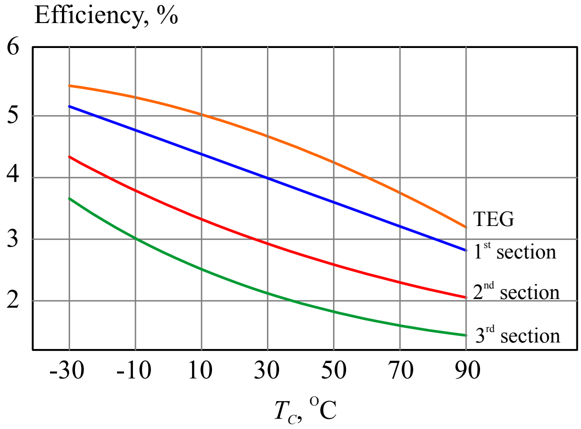

Fig. 7. The efficiency of sections and the integral TEG efficiency versus the cold temperature of TEG.

Fig. 7 shows the efficiency values of each of the three TEG sections and the integral TEG efficiency versus the cold temperature of TEG.

Fig. 8 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 ~14%...24% of thermal generator power. Fig. 9 shows the electric power of TEG versus ambient temperature with regard to expenditures on heat removal.

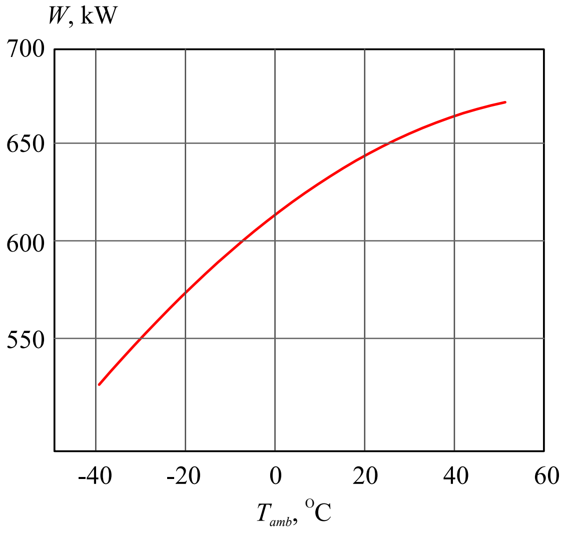

Fig. 8. The optimal electric power of TEG cooling system versus the ambient temperature.

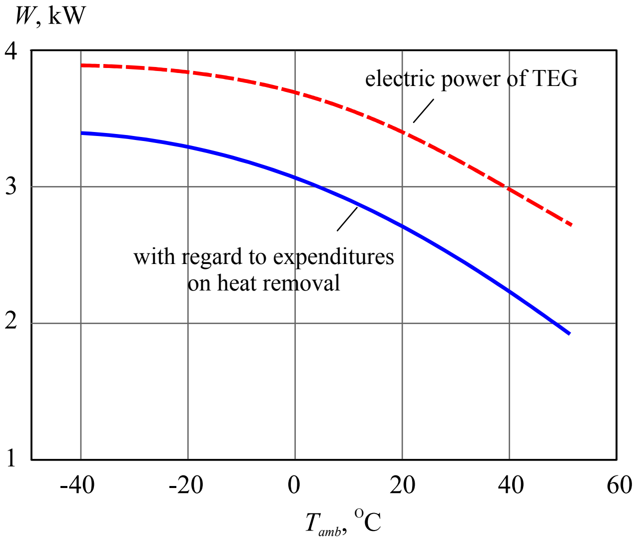

Fig. 9. The electric power of TEG versus the ambient temperature.

Fig. 10 compares the efficiency of one-section TEG [3] and three-section TEG analyzed in the present paper.

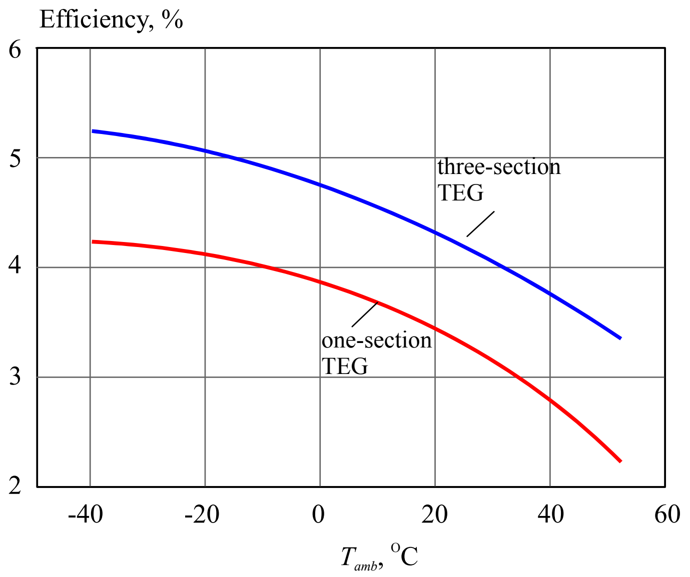

Fig. 8.The efficiency of TEG versus the ambient temperature.

It is seen that the use of generator sections, under otherwise equal conditions, yields better efficiency values. The use of sections assures 1.2 -1.4 times higher efficiency of TEG. According to the results of [3], this can give fuel saving about 3-7%.

Conclusions

1. A physical model of three-section thermoelectric generator for a car with a diesel engine has been created. The presence of three sections has been previously substantiated while investigating a multi-section generator. A mathematical description of three-section generator has been made and software for its study and optimization has been developed.

2. The efficiency of computer simulation has been demonstrated by a case study of a generator for a car with a 75 kW diesel engine. The optimal hot temperatures of sections have been obtained as a function of the cold temperature of TEG in the range of –30…+90^{O}C. It has been established that with increasing the cold 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 electric energy expenditures on heat removal have been determined. It has been established that these expenditures increase from 530 W to 670 W with a rise in ambient temperature from –40^{O}C to +50^{O}C.

4. The power of TEG as a function of ambient temperature has been determined. It has been established that the highest power value (~4 kW) is achieved at $T_{amb} = -40$ ^{O}C and reduced to 2.8 kW at $T_{amb} = +50$ ^{O}C. Part of this energy is spent on heat removal from TEG. With regard to these expenditures, the generator power at $T_{amb} = -40$ ^{O}C is 3.2 kW and reduced to 2 kW at $T_{amb} = +50$ ^{O}C.

5. The efficiency of sections and the integral efficiency of TEG have been found as a function of the cold side temperature of TEG. The highest efficiency values occur on the first section to which the exhaust gas from the engine is fed directly. The efficiency varies from ~5% to 3% with a change in TEG cold temperature in the range of –30…+90^{O}C. The next section to which the gas that passed through the first section is fed has the efficiency values from 4.3% to 2%. The third section which utilizes the heat of exhaust gases that passed through the first and second sections yields the lowest efficiency values in the

range of 3.6…1.4%. In so doing, the integral efficiency is the highest at $T_C = -30$ °C and makes ~5.5%. It is reduced to 3.2% at $T_C = +90$ °C.

6. A comparison of the efficiency of one-section and three-section generators demonstrates efficiency increase with the use of three sections from 4.2% to 5.2% at $T_{amb} = -40$ °C. The efficiency of three-section generator also remains higher at elevated ambient temperatures. At $T_{amb} = +50$ °C the efficiency of three-section TEG is 3.3%, while the efficiency of one-section TEG is as low as 2.2%.

7. In general, the above studies demonstrate the advantages of three-section TEG in the electric power and efficiency by a factor of 1.2…1.4. The results obtained also prove the fact that a TEG for a diesel engine is more efficient when operated at low ambient temperatures. The electric energy expenditures on heat removal from TEG are minimal as well.

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