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EFFECT OF AIR COOLING ON THE EFFICIENCY OF THERMOELECTRIC GENERATOR IN A DIESEL-ENGINED CAR

A model of a car with thermoelectric generator (TEG) was created with regard to the fact that TEG must assure power supply to heat removal system of its own. The results of optimization of the hot side temperature of TEG and the electric supply power of heat removal system are given. The effective efficiency and the electric power of TEG for a 75 kW diesel engine are calculated. The necessity of optimal design of TEG heat removal system is shown.

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

Introduction

The use of waste heat from the internal combustion engines is one of the critical tasks of thermoelectricity [1 – 6]. World producers of vehicles, as well as companies of thermoelectric profile, give much prominence to the development of efficient thermoelectric generators for vehicles. The purpose is to increase fuel saving due to the use of engine exhaust heat for electric energy generation.

The largest companies making it their mission to create industrial prototypes of generators and their large-scale production are Hi-Z [7], BSST [8] and General Motors [9] in the USA. In Japan, the problems of creating automotive generators are most widely addressed by companies Komatsu [10], Nissan [11] and Shiroki [12]. In Germany, company Volkswagen [13] and company BMW together with DLR (German Airspace Centre) represented their developments of thermoelectric automotive generators [13]. Nevertheless, it should be noted that the majority of the above works disregard the effect of thermoelectric generator itself on the operation of a vehicle. However, as is known, the presence of a thermoelectric generator has a considerable impact on the operation of a car due to at least three factors, namely additional hydraulic resistance in vehicle exhaust system, mechanical expenditures of engine on the transportation of additional mass of TEG proper and the expenditures related to the necessity of heat removal from thermoelectric generator. In [4-6] the efficiency of TEG with regard to transportation costs is discussed in detail. It is shown that for cars these costs can exceed the effective work of TEG. As regard heat removal, for the purpose of noninterference to automotive cooling system, heat removal from TEG should be done due to TEG own power.

The purpose of this work is to estimate the effective power and efficiency of an automotive thermoelectric generator with regard to provision of TEG heat removal.

Physical model of a car with thermoelectric generator

The work of thermoelectric generator as part of modern car can be represented by a schematic shown in Fig. 1.

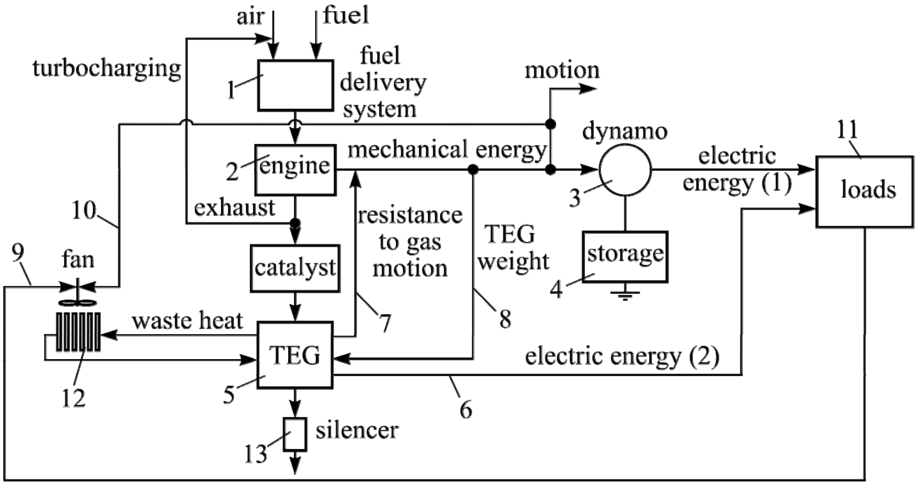

Fig. 1. Schematic of energy distribution in a car with TEG.

Fuel delivery system 1 feeds into engine 2 fuel mixture whose combustion provides for mechanical power of engine P. This power is spent on driving the car itself P_A and on the work of dynamo 3 that generates electric power W_D at efficiency η_D. The electric power is spent on the work of all car electric loads 11 and on charging storage 4.

The thermoelectric generator 5 will offer an additional advantage of generated electric power W_{TEG} 6. Additional expenditures will include: mechanical power P_{gas} 7 related to pressure increase in the exhaust system; mechanical power P_m 8 related to car weight increase due to TEG; electric 9 (or mechanical 10) power P_c necessary for provision of TEG cooling system operation.

Thus, the energy balance in a car without TEG is of the form:

$$P = P_A + W_D / \eta_D. \quad (1)$$

The energy balance in a car with thermoelectric generator is given below

$$P + W_{TEG} / \eta_{TEG} = P_A + W_D / \eta_D + P_c + P_m + P_{gas}, \quad (2)$$

where η_{TEG} is thermoelectric generator efficiency, P_c is mechanical power spent on provision of TEG cooling system operation, P_m is mechanical power spent on the transportation of TEG, P_{gas} is mechanical power spent on overcoming additional pressure in exhaust system due to the existence of TEG.

Let us consider a simplified model of a car with TEG with regard to provision of heat removal from TEG (Fig. 2) that will enable us to reveal in general terms the basic features of heat removal from TEG.

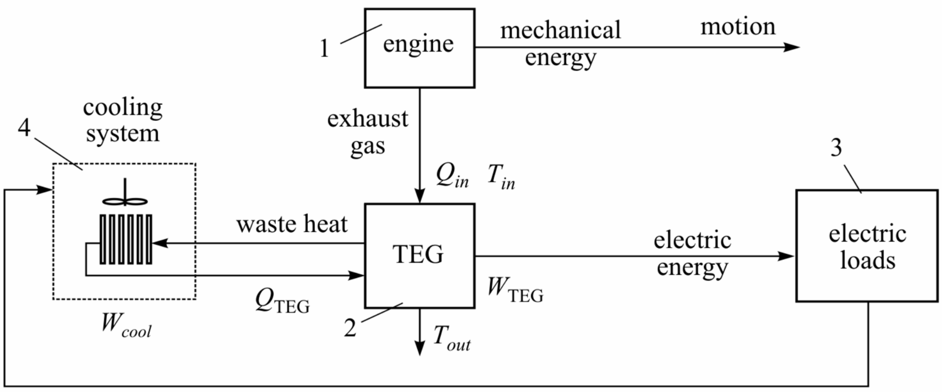

Fig. 2. A simplified model of a car with TEG.

Exhaust gas of thermal power Q_{in} from engine 1 comes to thermoelectric generator 2 of thermal resistance R_t at temperature T_{in} and leaves the generator at temperature T_{out}. The TEG generates electric energy W_{TEG} at efficiency η_{TEG}. A case is considered when part of this electric energy W_{cool} is spent on the operation of cooling system 4 which removes thermal power Q_{TEG} from the TEG. The ambient temperature is T_{amb}. The problem thus stated brings into existence two values that should be optimized, namely the hot side temperature of TEG and the power spent on the operation of cooling system.

The model is concerned with a one-sectional TEG and ignores the effect of other vehicle systems on the engine performance.

Mathematical description of thermoelectric generator operation

Equation for finding the optimal hot side temperature of TEG will be found from the heat balance in TEG:

$$Q_{in} = Q_{out} + Q_{TEG}, \tag{3}$$

$$Q_{in} = cm\left(T_{in} - T_{amb}\right), \tag{4}$$

$$Q_{out} = cm\left(T_{out} - T_{amb}\right), \tag{5}$$

$$Q_{TEG} = \frac{T_{out} - T_0}{R_t}, \tag{6}$$

where c is exhaust gas heat capacity, m is exhaust gas mass flow rate, T_0 is the cold side temperature of TEG.

Substituting (4) – (6) into (3), we obtain an equation for finding the hot side temperature of TEG:

$$T_{out}\left(R_t\right) = \frac{Q_{in}\left(1 + \dfrac{T_{amb}}{T_{in} - T_{amb}}\right) + \dfrac{T_0}{R_t}}{\dfrac{1}{R_t} + \dfrac{Q_{in}}{T_{in} - T_{amb}}}\ . \tag{7}$$

TEG efficiency will be calculated by the formula

$$\eta_{TEG}(R_t) = \frac{T_{out} - T_0}{T_{out}} \frac{M - 1}{M + T_0 / \mathrm{T}_{out}}\ , \tag{8}$$

$$M = \sqrt{1 + Z\frac{(T_{out} + T_0)}{2}}, \tag{9}$$

The effective efficiency of TEG was found as follows:

$$\eta_{ef} = \frac{W_{TEG} - W_{cool}}{Q_{TEG}}. \tag{10}$$

The temperature dependence of figure of merit Z in formula (9) was taken into account by using the average integral value in the temperature range (T_0, T_{out}).

To calculate the electric power of TEG with account of heat removal system operation, it is necessary to know the efficiency of air-to-liquid heat exchanger obtained from the experimental studies of heat exchanger:

$$Q_{cool} = f\,(W_{cool}, T_H, T_C), \tag{11}$$

where Q_{cool} is thermal power of heat exchange system, W_{cool} is electric supply power of heat exchange system, T_H is liquid temperature, T_C is air temperature.

Optimization algorithm was realized in MathCAD mathematical simulation system [14].

TEG parameters calculation example

As an example, we shall calculate the basic parameters of TEG for a 75 kW diesel in continuous operation mode at a car speed 100 km/h. In this operation mode, the exhaust gas temperature is about 420 °C.

Thermoelectric materials. Calculation of TEG efficiency and power was made with the use of a typical temperature dependence of *ZT* [15] of *Bi-Te* based materials which is given in Fig. 3.

Air-to-liquid heat exchanger. The empirical dependence (11) characterizing the work of heat exchange system was found experimentally according to the following schematic (Fig. 4).

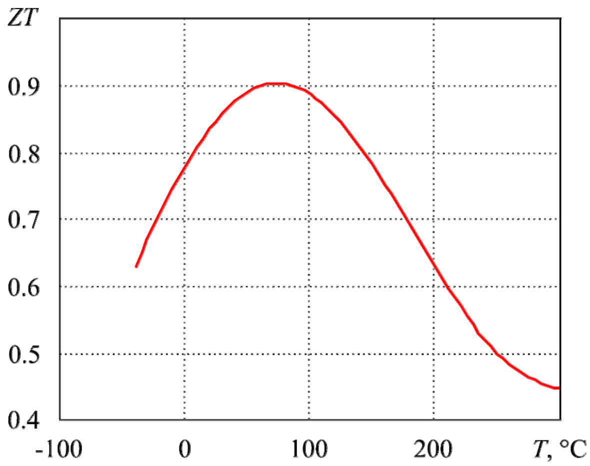

Fig. 3. Temperature dependence of ZT for Bi-Te based materials.

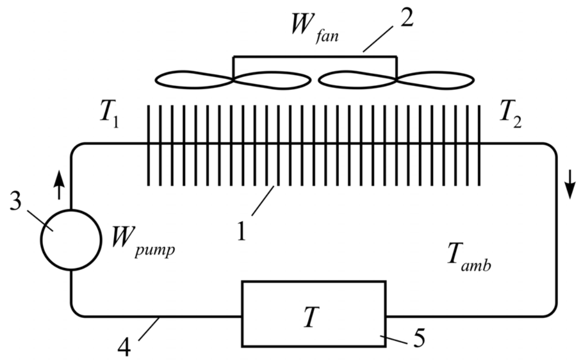

Fig. 4. Schematic of cooling system study: 1 – air-to-liquid heat exchanger, 2 – fan unit, 3 – electric liquid pump, 4 – liquid circuit, 5 – liquid thermostat.

Liquid thermostat 5 was used to create temperature difference between the liquid and the environment. Pump 3 pumped the liquid through heat exchanger 1 blown over by fan unit 2. The difference in temperatures T_1 and T_2 was used to determine power Q removed by the heat exchanger depending on liquid temperature T, supply power of fan unit W_{fan} and supply power of pump W_{pump}.

The results of experimental study of heat removal system are given in Fig. 5.

A series of such dependences of heat exchanger thermal power for different supply powers of fans and pump was polynomial approximated and used in optimization algorithm.

As a rule, the efficiency of fans, just as the efficiency of pumps, is not very high (50 – 65 %). So, the use of direct cooling from the incoming flow can assure a smaller expenditure of engine energy on cooling system (by a factor of ~2 – 2.5). Many works predict the use of liquid heat exchangers (radiators) existing in vehicles for cooling of thermal generator. However, in this case it should be noted that such heat exchangers are designed for provision of heat removal from the engines under the most complicated conditions, namely high temperature of incoming air flow, low motion speeds, extreme powers. Under such conditions, the existing radiators can be unable to remove heat from thermal generator without disturbance of engine thermal conditions. Therefore, it may be necessary to use special heavy-duty radiators that will assure heat removal from thermal generator, or to use an additional heat exchanger for heat removal from TEG. In so doing, it should be expected that the use of electric fans for the operation of heat removal system makes this operation mode more flexible and can assure minimum electric energy consumption.

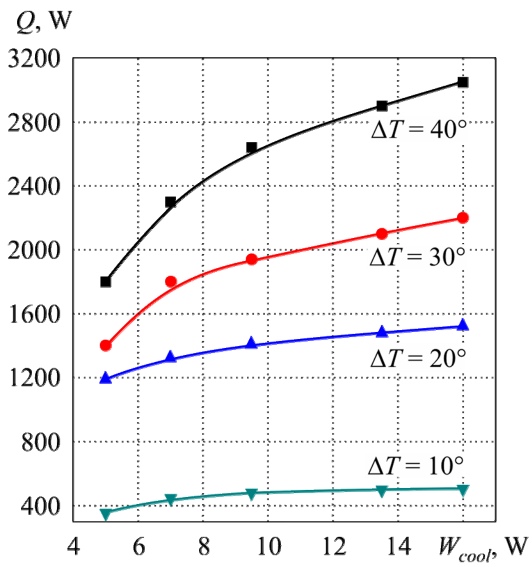

Fig. 5. Dependences of heat removal power of air-to-liquid heat exchanger on the supply power of fans. Pump power is 2 W.

Heat removal system optimization. In the beginning, optimization of the hot side temperature of TEG took place. The results of this optimization are shown in Figs. 6 – 7. As is obvious, there exists TEG power optimum which is due to the effect of two competing factors. With a reduction of TEG thermal resistance, the thermal power passing through the generator is increased. At the same time, the hot side temperature of TEG is reduced.

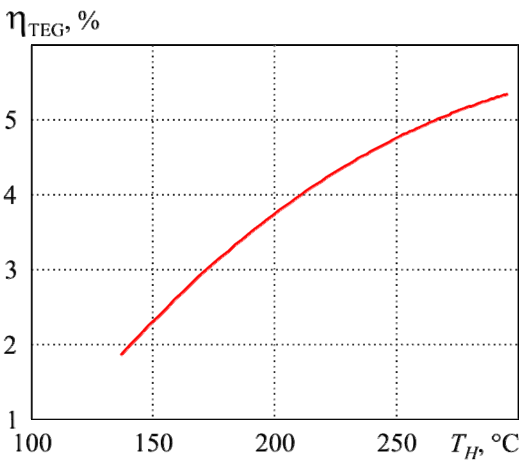

Fig. 6. Dependence of TEG efficiency on the hot side temperature of TEG. T_c = 90 °C.

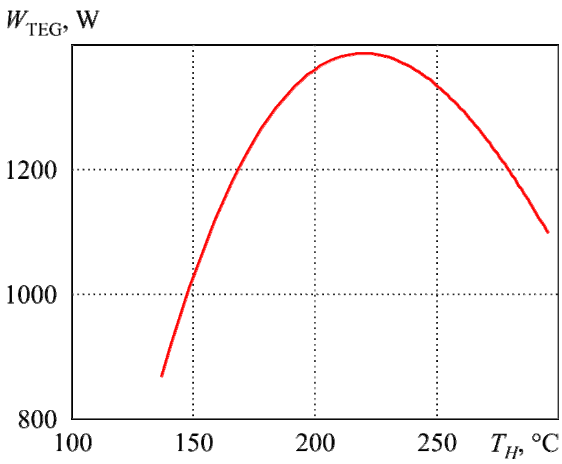

Fig. 7. Dependence of TEG electric power on the hot side temperature of TEG. T_c = 90 °C.

Calculation of the effective efficiency and power of TEG with regard to expenditures on heat removal was performed according to Eqs. (6 – 8).

Figs. 8 – 9 show the results of optimization of heat removal system. The effective efficiency and electric power of TEG were calculated with consideration that part of TEG power is removed to provide for the operation of TEG heat removal system. From the plots it is evident that there exist pronounced optimal operating conditions of heat removal system. From Fig. 8 it is seen that with a reduction of ambient temperature, the efficiency of TEG increases from ~3.8 % at a temperature of +50 °C to ~ 7.2 % at a temperature of –40 °C. It corresponds to the extreme values of TEG electric power 1.2 kW and 3.1 kW, respectively. From Fig. 9 it is seen that TEG yields additional 1.5 – 4 % of engine power in the form of electric energy. With regard to dynamo efficiency, it will correspond to 2 – 6 % of fuel saving.

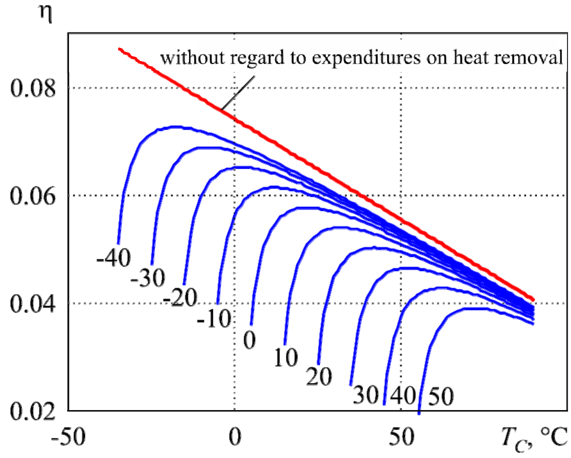

Fig. 8. Dependence of TEG effective efficiency on the cold side temperature of TEG. Ambient temperature is indicated beside the plots.

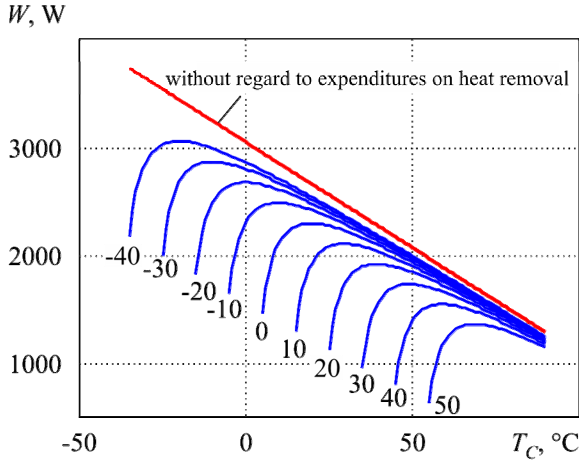

Fig. 9. Dependence of TEG effective electric power on the cold side temperature of TEG. Ambient temperature is indicated beside the plots.

Table 1 lists the data on the optimal values of TEG efficiency and power, as well as thermal power that must be removed from TEG and expenditures on cooling system operation. As can be seen, with a rise in ambient temperature, the optimal effective efficiency and power decrease, and expenditures on cooling system operation increase from ~ 15 % to ~ 25 % with the use of electric fans. If the fans are driven by engine mechanical energy, then with regard to average electric fan efficiency, expenditures on cooling system operation will make 6 – 12 %.

Table 1

Basic characteristics of TEG with heat removal system

Ambient temperature, °C	Thermal power that must be removed from TEG, kW	TEG power, kW	Electric power of heat removal system, kW	Electric expenditures on heat removal operation, %	Effective efficiency of TEG, %
-40	42.7	3.12	0.477	15.4	7.25
-30	41.1	2.84	0.462	16.5	6.80
-20	40.0	2.61	0.457	17.4	6.53
-10	38.0	2.32	0.432	18.7	6.05
0	36.5	2.15	0.422	20.1	5.75
10	33.9	1.82	0.365	20.4	5.30
20	32.0	1.60	0.337	21.1	5.05
30	31.4	1.41	0.315	22.5	4.61
40	31.5	1.32	0.304	23.4	4.25
50	31.5	1.21	0.297	24.8	3.82

Let us consider what changes can take place in TEG efficiency versus the car location.

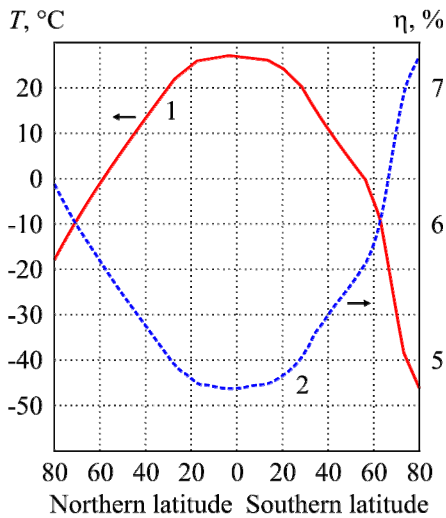

Fig. 10. Dependences of average annual temperature and TEF efficiency on the latitude.

Fig. 10 shows the average annual temperature on the planet (curve 1) depending on the latitude. Another scale shows the latitude dependence of thermoelectric generator efficiency (curve 2) [16].

Conclusions

1. Arrangement of heat removal from an automotive thermal generator is an important factor of its performance deficiency that should be taken into account in the design of such TEG. Thus, for a 75 kW diesel engine the expenditures on heat removal from a one-sectional TEG by heat exchangers with electric fans can reach 15 – 25 % of electric energy generated by TEG, or approximately 6 – 12 % of TEG power in the form of engine mechanical energy which is about 0.1 – 0.4 % of its power.
2. The efficiency of heat removal from an automotive TEG has optimal values that are a function of ambient air temperature. For a diesel engine, with a reduction of ambient air temperature, the efficiency of TEG increases from ~ 3.8 % at a temperature of + 50 °C to ~ 7.2 % at a temperature of – 40 °C, which corresponds to TEG electric power values 1.2 kW and 3.1 kW. So, car operation with TEG is more efficient in climatic zones with reduced air temperatures.
3. The use of TEG with account of expenditures on heat removal from it yields additional 1.5 – 4 % of engine power in the form of electric energy, which, respectively, can effect fuel saving about 2 – 6 % at a car speed 100 km/h.

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