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THERMOELECTRIC GENERATOR FOR TRUCKS

The results of computer simulation of thermoelectric generators (TEG) using the exhaust heat of internal combustion engines were presented. The simulation was done with regard to dynamic modes of engine operation on the basis of real records of monitoring system with the use of real parameters of thermoelectric modules.

Key words: thermoelectric generator, internal combustion engines.

Introduction

The use of waste heat from the internal combustion engines is one of the critical tasks of thermoelectricity. World producers of vehicles, as well as companies of thermoelectric profile, give much prominence to the development of efficient automotive thermoelectric generators [1 – 8]. The purpose is to increase fuel saving up to 10 % 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, BSST and General Motors in the USA. In Japan, the problems of creating automotive generators are most widely addressed by companies Komatsu, Nissan and Shiroki. In Germany, company Volkswagen and company BMW together with DLR (German Airspace Centre) represented their developments of thermoelectric automotive generators.

The lack of broad application of automotive TEG is attributable to insufficiently high generator efficiency. The generator efficiency essentially depends on the engine operating mode. The dynamic modes of engine operation during an actual drive impose fairly complicated requirements to design and optimization of automotive generators that cannot be fully met so far. One of optimization components is TEG design for a specific engine type and its priority operating mode. Particular attention is claimed by trucks with heavy engines and, accordingly, large amount of exhaust heat.

The purpose of this work is to design a thermoelectric generator which utilizes the exhaust heat of truck engine.

Optimization of a thermoelectric generator is done by computer design [10] which is as follows.

Computer design procedure

Let us consider a physical model of thermoelectric generator (TEG) shown in Fig. 1. In the general case a TEG is composed of N sections connected in series with respect to hot gas flow and cold heat carrier.

Each TEG section comprises the following components (Fig. 1): hot heat exchanger (1), thermopile (3) with thermal resistance $R_t^{(i)}$ and efficiency $\eta(T_H, T_0)$; cold heat exchanger (4) with temperature T_0; thermal resistance between the hot heat exchanger and thermopile $R_t^{(i)}$ (2), which restricts the hot side temperature of modules. The thermopiles of each section are closed to the matched electric load R_i (5).

The inlet hot gas flow is characterized by 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 the outlet of TEG, gas temperature is T_H^{out} and thermal power is Q_H^{out}. The heat from the hot heat exchanger is transferred through thermal resistance $R_t^{(i)}$ to thermopile, heating its hot side to temperature $T_H^{(i)}(x)$.

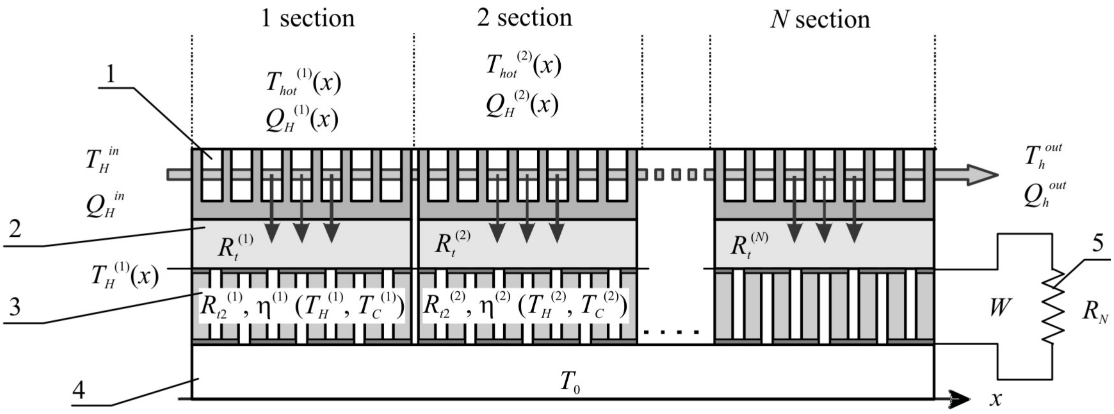

Fig. 1. Physical model of thermoelectric generator:
1 – hot heat exchanger; 2 – thermal resistance between the hot heat exchanger and thermopile; 3 – thermopile; 4 – cold heat exchanger; 5 – matched electric load.

To avoid overheating of thermoelectric modules, the physical model will be supplemented with a bypass through which the excess exhaust gas will be rejected so as to maintain the temperature of modules on maximum permissible level.

For the optimization of TEG it is necessary to find the distribution of temperatures and heat fluxes in each section. Such calculation for this model was done by using numerical computer methods.

For the calculations of TEG electric power we use energy balance equation in the form

$$W = \sum_{i=1}^{N} \left[\int \left(Q_H^{(i)}(x) - Q_C^{(i)}(x) \right) dx \right]. \tag{1}$$

The necessary temperatures and heat flows are found from thermal conductivity equation

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

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

The boundary conditions for (2) will be given by

$$Q_H^{in(1)} = Q_H^{in}, \; Q_H^{in(i+1)} = Q_H^{out(i)}, \; Q_H^{out(N)} = Q_H^{out}, \tag{3}$$

$$Q_H^{(i)}(x) = \left(T_H^{(i)}(x) - T^{(i)}(x) \right) / R_t^{(i)}, \tag{4}$$

$$Q_C^{(i)}(x) = \left(T_0 \,(x) - T^{(i)}(x) \right) / R_{t2}^{(i)}, \tag{5}$$

A set of relations (1) – (5) allows determining the distribution of temperatures $T_H^{(i)}(x)$ and thermal flows $Q_H^{(i)}(x)$ in each section.

To restrict the hot temperature of module, thermal resistance $R_t^{(i)}$ between the hot heat exchanger and thermoelectric module is found from equation (4).

The power of each section and general efficiency of TEG can be found from equations

$$W^{(i)} = \int Q_H^{(i)}(x)\eta(T_H^{(i)}(x), T_0)dx\,, \tag{6}$$

$$\eta_{TEG} = \frac{1}{Q_H^{in}}\sum_{i=1}^{N} W^{(i)}\,. \tag{7}$$

The system of equations (1) – (5) is solved by numerical methods on a two-dimensional finite element mesh [10].

Computer design results

Design of a thermoelectric generator in a dynamic mode was performed with the use of exhaust gas input parameters (temperature and flow rate) obtained on the exhaust system of truck CAT 775F for engine Navistar 13 L [11] of power 330 kW for different engine modes:

1 – performing standard tasks by truck.

2 – operation of truck engine at close to nominal load (speed – 1500 RPM, turning torque – 1100 N·m).

Fig. 2 shows the exhaust gas temperature, Fig. 3 – the exhaust gas flow rate for the case of engine operation at nominal load.

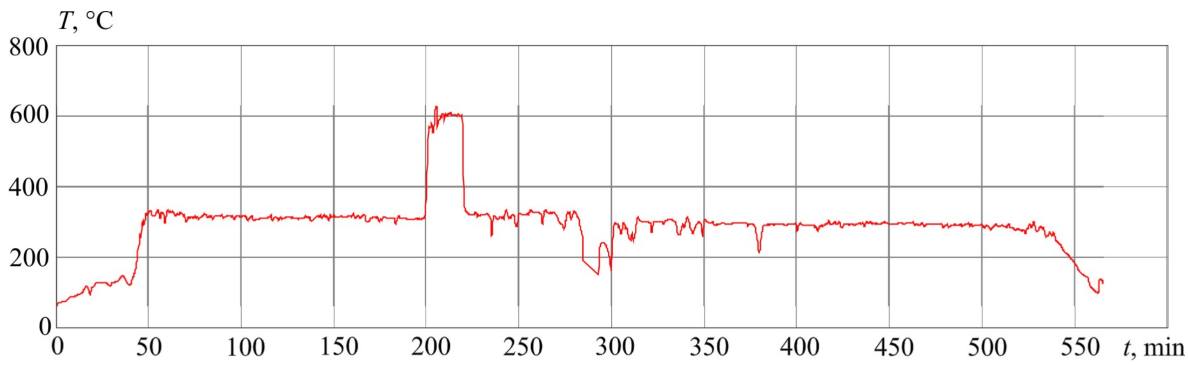

Fig. 2. Exhaust gas temperature for engine nominal operation.

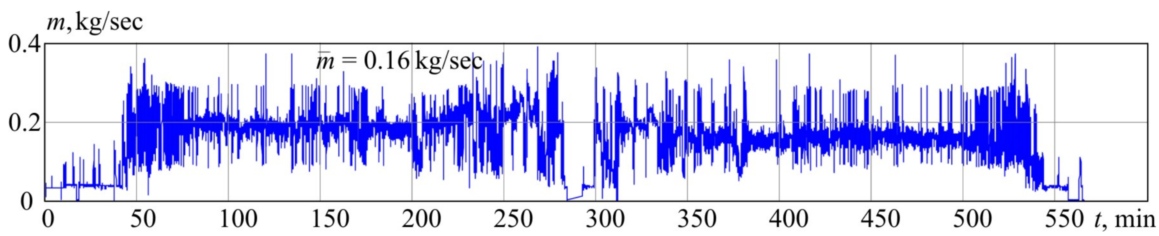

Fig. 3. Exhaust gas flow rate for engine nominal operation.

To design a generator, the thermoelectric modules ALTEC-1061 [17] based on *Bi-Te* were selected that outperform known world analogs.

The generator design optimization consisted in determining the minimum number of modules necessary for achievement by the generator of maximum average electric power within the operating cycle represented in Fig. 2 – 3. Fig. 4 shows the results of this optimization.

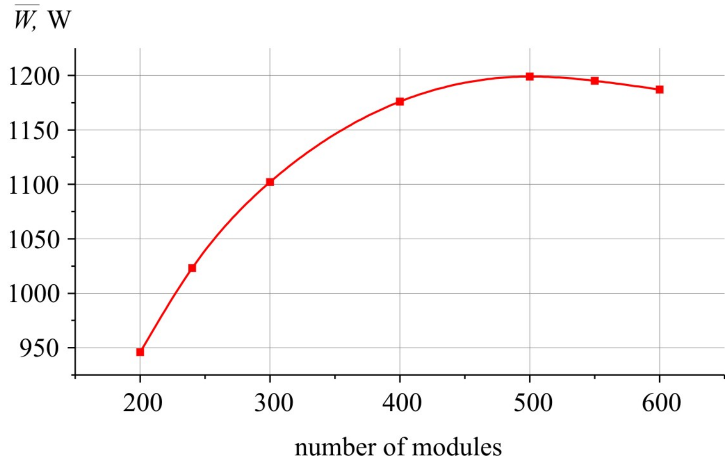

Fig. 4. Dependence of the average electric power of TEG on the number of modules.

It can be observed that for the task in hand the optimal number of modules is ~ 500. With a downward deviation from the optimal value the hot side temperature of modules can be raised to higher values, however, the total electric power of TEG drops due to small number of modules. A drop in the electric power of TEG is also observed with an upward deviation from the optimal number of modules. This is due to a decrease in total thermal resistance of thermopile, and, as a consequence, a decrease in temperature difference on the modules.

Fig. 5 shows time dependences of the hot side temperature of modules. The cold side temperature is assumed to be T_0 = 60 ºC.

Fig. 6 shows time dependence of the electric power of TEG. The average electric power throughout the cycle was ~ 1200 W.

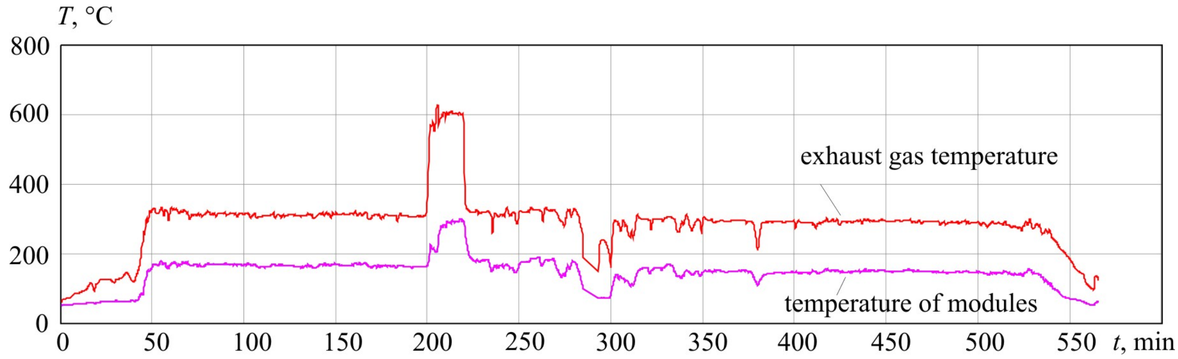

Fig. 5. Time dependence of the hot temperature of modules for engine nominal operation.

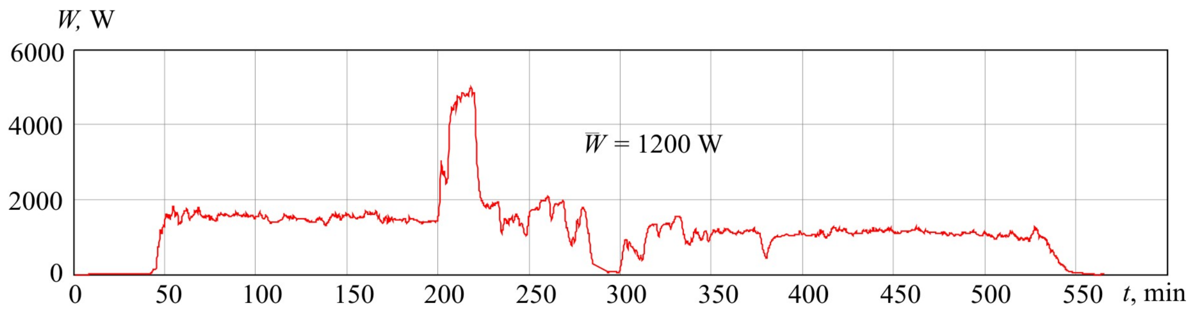

Fig.6. Electric power of TEG for engine nominal operation.

In so doing, the average efficiency of thermoelectric generator in one cycle is 2.2 %.

Generator optimization for alternative mode of operation – performing standard tasks by truck – yielded the following results.

Fig. 7 shows the result of optimization of the average electric power of TEG in one complete operating cycle.

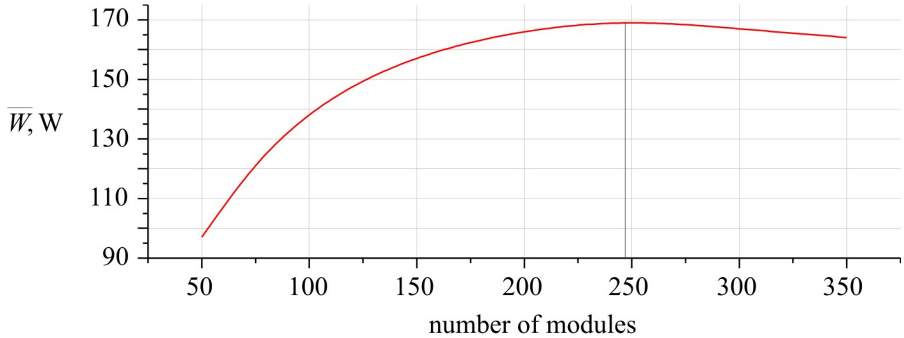

Fig. 7. Dependence of the average electric power of TEG on the number of modules.

Fig. 8 shows time dependences of the hot side of modules when performing standard tasks by truck. The cold side temperature is assumed to be T_0 = 60 ºC. Fig. 9 shows the electric power of TEG in this operating mode.

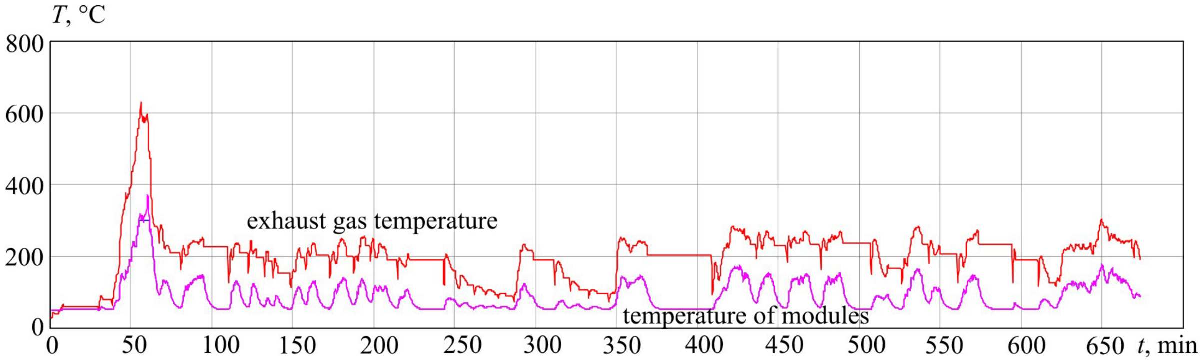

Fig. 8. Time dependence of gas temperature and the hot temperature of modules.

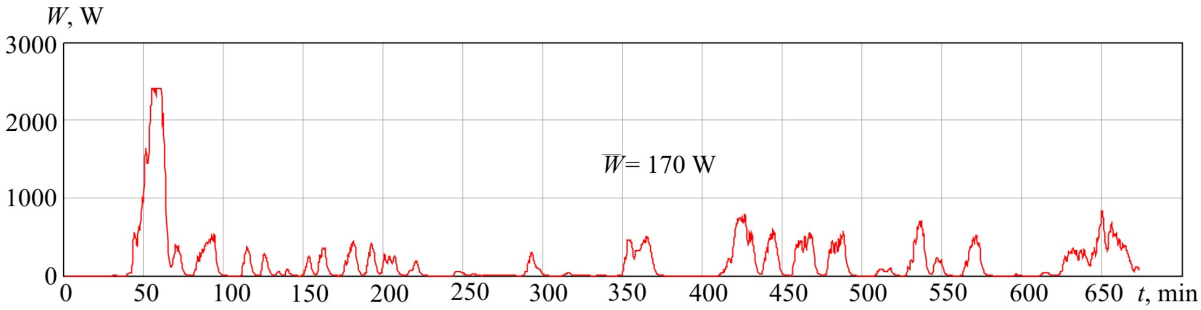

Fig. 9. Electric power of TEG.

A TEG optimized for this operating mode comprises ~ 250 thermoelectric modules and develops average electric power 170 W. The efficiency of TEG in this case is 1.7 %. Such a low value is caused by low exhaust gas temperatures.

Conclusions

1. A thermoelectric generator for truck diesel engine of power 330 kW was designed for nominal

load operation of engine and for the mode of performing standard tasks by truck.

2. It was shown that at nominal load operation of engine the TEG can produce on the average ~ 1200 W of electric energy at efficiency 2.2 %.
3. When performing standard tasks by trucks, the average electric power developed by TEG is 170 W and efficiency 1.7 %. The low values of power and efficiency are caused by low temperature of truck exhaust gases.

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