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Effect of a Thermoelectric Generator on the Fuel Economy of a Vehicle Operating in a Real-world Environment

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This paper presents a study of how a thermoelectric generator can affect the vehicle fuel efficiency in a real-world environment. Real-world drive cycles are significantly different from the standard cycles, which certainly has a negative impact on fuel economy. Given low share of hybrid vehicles, it is advisable to assess the impact of a thermoelectric generator, which partially recovers thermal energy of exhaust gases, on fuel efficiency of a vehicle with a conventional power plant. Tests were run at actual vehicle routes and involved registration of thermodynamic parameters of exhaust gas and coolant in addition to the basic parameters of the vehicle and its internal combustion engine. The results were used to calculate the electric output of the thermoelectric generator at each moment of time, which allows to evaluate its effect on the fuel economy of the vehicle as a whole. The results showed an improvement of the internal combustion engine fuel consumption of about 3% after installation of a thermoelectric generator, which is significantly less than known simulation results based on standard driving cycles. It can be explained by sudden powerful accelerations of the vehicle during the test drives as well as other factors.

Key words: Thermoelectric generator, Recuperation of heat energy, Direct conversion of heat into electricity, fuel consumption reduction.

Energy efficiency of a vehicle, which is mainly judged by fuel economy, depends mostly on the degree of conversion of the combustion energy into mechanical and/or electrical (in hybrid vehicles) energy. Modern technologies of organizing ICE (internal combustion engine) operation processes, used in road transport, approach their ultimate limits. Further improvement of such technologies will be accompanied by growing technical difficulties and yield progressively less effect. To further increase the efficiency of power plants based on heat engines, it is necessary to introduce new technologies of converting the fuel combustion energy, including thermal energy of exhaust gases, which is thrown away into the atmosphere. At the same time, up to 40% of the consumed fuel energy is irretrievably lost with the exhaust gases alone (Bourhis and Leduc, 2010; Jadhao and Thombare, 2013). Therefore, thermal energy of the exhaust gases is the most promising way of increasing fuel efficiency by partial recuperation (Jianqin et al., 2011). Recovery of ICE exhaust gas thermal energy can be implemented by thermodynamic, thermochemical or thermoelectric methods.

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Thermodynamic recovery of exhaust gas heat, carried out with the help of devices using the Rankine or Erickson cycles or Stirling engines (Nadaf and Gangavati, 2014), produces mechanical energy, which has very limited practical application. There are also methods of thermochemical recuperation, producing fuel with increased hydrogen contents and high calorific value, which is used for fueling an internal combustion engine, such as endothermic decomposition of methanol into synthesis gas (Khripach, 2004). Implementation of thermochemical recuperation presupposes introduction into the vehicle design of not only the conversion reactor, but also an additional tank for storing the source substance for the synthesis gas generation, which greatly increases the cost of the vehicle.

Thermoelectric recuperation based on the Seebeck effect, lithium hydride cycle, thermionic emission, and other principles allows to obtain electrical energy, which can be used to power electrical accessories and, in hybrid vehicles, to feed traction motors driving the wheels . Each of the thermoelectric exhaust gas heat recovery methods has both obvious advantages and certain significant disadvantages (Legros et al., 2014). An undeniable advantage of the thermoelectric exhaust heat recovery by using generator modules based on the Seebeck effect is absence of moving parts and, consequently, silent operation. The disadvantage is high cost of the module, however, given the unceasing interest for developments in this area and results of research in the field of thermoelectric materials production, it could be assumed that they will get significantly cheaper in the coming years (Ismail and Ahmed, 2009).

The electricity resulting from partial exhaust heat recovery can be used for various purposes. For example, in a hybrid vehicle it can be directed to the traction electric motor or to the energy storage. The use of the obtained energy is difficult in vehicles with internal combustion engines, but it can still be used to supply the on-board electrical network or recharge the battery. In such case, the load on the generator of an internal combustion engine can be significantly reduced, and sometimes completely eliminated. Taking into account relatively low conversion efficiency in the generator, it will significantly reduce fuel consumption of an internal combustion engine.

The quoted studies, which simulate operation of a thermoelectric generator with different parameters of heat carriers without being tied to a specific vehicle (Kumar et al., 2013; Anatychuk et al., 2011) and as part of a vehicle, in particular a hybrid one (Deng et al . 2014; Tatarinov et al., 2013), showed the possibility to reduce the fuel consumption of an internal combustion engine by 6.9%, if the vehicle follows the standard NEDC (New European Driving Cycle**)** cycle. Real-world drive cycles are significantly different from the standard cycles, which certainly has a negative impact on fuel economy. Given low share of hybrid vehicles, it is advisable to assess the impact of the thermoelectric generator, which partially recovers thermal energy of exhaust gases, on the fuel efficiency of a conventional vehicle in the real-world environment.

This makes it necessary to conduct tests at real vehicle routes, registering not only the basic vehicle and internal combustion engine parameters, but also thermodynamic parameters of the exhaust gas and coolant. The results obtained can be used to calculate the amount of electric power generated by the TEG (thermoelectric generator) at every moment, which allows to assess its impact on the fuel efficiency of the vehicle as a whole and optimize the TEG control algorithms (Grane et al., 2013).

METHOD

Analysis of energy flows in a vehicle

Analysis of the ICE heat balance shows that up to 40% of the energy released during fuel combustion is carried away with the exhaust gases. Much of this energy could be made useful for different purposes. Besides, part of the energy is dissipated by the ICE's cooling system or gets spent to overcome the internal friction and inertial forces.

Figure 1 shows a scheme of the energy flows inside a vehicle equipped with an internal combustion engine and changes caused by introduction of a thermoelectric generator into the design.

The schemes provide grounds to derive a formula describing the relative power of the energy flows in a vehicle driven by an internal combustion engine, and modify it to take into account the effects of adding a thermoelectric generator for partial recovery of the exhaust gas thermal energy.

The relative power of the energy flows shown in Figure 1a can be written as the formula:

$$N_{ICE} = N_{veh} + N_{gen} + N_{ex} + N_{cool} + N_{oth.los.} \quad ...(1)$$

It should be noted during an analysis of the formula that the energy lost with the exhaust gases, in the cooling system and various other losses are dependent on the total amount of energy produced by the fuel combustion in an internal combustion engine and their balance and share in the total sum largely depends on the engine operation mode. On the other hand, the total energy, and hence the amount of fuel consumed, directly depends on consumption of mechanical power by the crankshaft, which is the sum of the first two components in the formula (1).

Preparation of a formula describing the energy flows, shown in Figure 1b, requires a more complete description of some of its components and clarification of their dependencies for setting their numerical values during the process of simulation the movement of a vehicle equipped with a thermoelectric generator. So, the mechanical power needed to drive the generator of the internal combustion engine can be determined as the product of the combined power consumed by the vehicle's on-board electrical network at a given moment of time and the generator efficiency, which is shown by the formula (2). The efficiency of the generator depends on the rotation speed of the crankshaft, which drives the wheels with a constant transmission ratio, and the current load on the crankshaft. In this case, the vehicle's battery may become a consumer of the electricity. It happens when the voltage gets low and the charging process starts.

$$N_{gen} = N_{el} \cdot \eta_{gen} \quad ...(2)$$

After introduction of a thermoelectric generator into the vehicle design, part of the electricity needs of the vehicle is covered by generated energy. Thus, formula (2) is modified and can be written as follows:

$$N_{gen} = (N_{el} - N_{TEG}) \cdot \eta_{gen} \quad ...(3)$$

Taking into account constancy of the mechanical power spent to propel the vehicle and the use of the thermoelectric generator as a supplementary power source, the following equation can be written for the scheme in Figure 1b:

$$N_{ICE\,2} = N_{veh} + (N_{el} - N_{TEG}) \cdot \eta_{gen} + N_{ex\,2} + N_{cool\,2} + N_{oth.los.2} \quad ...(4)$$

As seen from the formula (4), at non-zero values of the thermoelectric generator power output the power at the crankshaft of an internal combustion engine will decrease, which changes its mode of operation and, accordingly, thermal and other losses. As a result, the fuel consumption of the internal combustion engine reduces. A special note should be made about the direct dependence of the power generated by the thermoelectric generator from the thermodynamic parameters of exhaust gases and coolant, which inevitably change when the mode of the internal combustion engine operation becomes different from the initial. This dependency can be obtained by simulating the TEG operation in various conditions, taking into account its design.

Simulation of the vehicle which follows the test route using a thermoelectric generator means that for each sequential moment of time the relative power of energy flows must be determined in accordance with formulas (3-4), and the current TEG power must be found by the procedure described in paragraph 2.2. Several iterations are needed until convergence criteria are met. The resulting total power value, which is, in fact, the amount of energy provided by fuel combustion, can be used to evaluate the fuel economy.

Method of calculating the heat flow power and TEG electric power

The thermoelectric generator considered in this study, the general design of which was developed earlier (Khripach et al., 2014), consists of the following main components: body, thermoelectric generator modules and liquid cooling system. Liquid cooling of thermoelectric generator modules is much more efficient than air cooling and allows to generate considerable total electric power (Zhou et al., 2013), which is directly proportional to the power of the heat flow from the exhaust gas to the coolant, which goes through the TGM.

Figure 2 shows a model of the considered thermoelectric generator for an automotive internal combustion engine in solid representation.

Exhaust gases after catalytic converter pass through the body of the thermoelectric generator, which has the form of a square tube with internal fins. The finning is optimized for increased heat transfer and uniform distribution of temperature fields. The cooling liquid is fed into the inlet ramp, where it is distributed between four coolers. The flows of exhaust gas and coolant go in different directions, thereby reducing the temperature gradient along the length of the thermoelectric generator and increasing the efficiency of conversion of thermal energy into electrical energy. Thermoelectric generator modules placed between the body and the coolers are thermally connected in parallel and electrically in series-parallel. Part of the thermal energy of the exhaust gas is passed through the thermoelectric generator modules to the coolant, which circulates in the coolers.

In general case, the thermoelectric generator can be presented as a combination of three components: a heat source, a thermoelectric module and a cooler. In the thermoelectric generator for automotive internal combustion engine exhaust gas is the source of thermal energy and the coolant of the engine is used to cool the generator. The scheme of thermoelectric generator's heat transfer model used in the calculation is shown in Figure 3.

The power of the heat flows can be determined on the basis of the heat transfer and thermal conductivity equations, resulting from the Newton-Richman law:

$$Q_1 = \alpha_1 \cdot A_1 \cdot \Delta T_1 \qquad ...(5)$$

$$Q_{TGM} = k_{TGM} \cdot A_{TGM} \cdot \Delta T_{TGM} \qquad ...(6)$$

$$Q_2 = \alpha_2 \cdot A_2 \cdot \Delta T_2 \qquad ...(7)$$

The heat transfer coefficients [alpha] from the hot and to the cold coolant, applied in these equations, depend on the type and temperature of the coolant, temperature difference, flow regime, state of the heat transfer surface and geometry of the heat exchanger. Therefore, they are functions of heat transfer and must be calculated independently at each time point (Lienhard and Lienhard, 2008; Lukanin and Shatrov, 2000).

Design of the heat exchangers has a significant influence on the heat flux from the hot and to the cold working fluid (Esarte et al., 2001), therefore our thermoelectric generator uses the optimized finning with variable height of fins and non-uniform grooves, which allows to attain TEG power of 1 kW at the exhaust gas temperature of 500 °C and the mass flow rate of about 35 g/s.

The average thermal conductivity of the thermoelectric generator modules, taking into account additional hot and cold walls, also depends on the design of the thermoelectric generator module and materials used. It can be determined by the formula:

$$k_{TGM} = \frac{1}{\frac{\delta_1}{\lambda_1} + \frac{\delta_{TGM}}{\lambda_{TGM}} + \frac{\delta_2}{\lambda_2}} \qquad ...(8)$$

At the same time, it is necessary to take into account separately the conversion of the thermal energy of the exhaust gas in the thermoelectric generator modules into electrical energy with certain efficiency, which depends on the temperature difference between the cold and hot junctions of the TGM (Meng et al., 2012):

$$Q_2 = Q_1 - N_{TGM} = Q_1 \cdot (1 - \eta_{TGM}) \qquad ...(9)$$

The given dependencies (5-9) and other laws, that apply to the processes of stationary heat and mass transfer, allow to determine the total heat flux from the exhaust gas to the coolant and, therefore, the electric power generated by the TEG. At the same time, the temperatures and pressures of the hot and cold fluids, as they pass through the heat exchangers, change considerably (Lu et al., 2013), which makes the heat flows uneven and significantly reduces the overall efficiency of the TEG

Tests of a vehicle in the real-world environment

Tests of a "Gazelle Next" light commercial vehicle equipped with a Nissan TD27T engine were conducted primarily to determine the fuel consumption in actual use. In addition to the basic parameters of the vehicle (speed, acceleration, etc.) and the internal combustion engine (engine speed, composition of the fuel mixture, fuel consumption, etc.) we logged readings from an exhaust gas temperature sensor at each measured parameters registration time point. The resulting data array, which includes temperatures and flow rates of the exhaust gas and the coolant, allows to evaluate the electric power, that can be generated by partial exhaust gas heat recovery in the considered thermoelectric generator.

Table 1 shows the technical data of the test object.

The tests were conducted at several routes, passing along regional roads of the Nizhny Novgorod region, primarily with suburban traffic, both in the forward and reverse directions. Figure 4 shows examples of the routes, where the test drives with fuel economy metering used in this study took place.

The tests were conducted during daylight and under normal weather conditions:

a) ambient temperature: 10-25 °C;
b) relative humidity: 45-80%;
c) atmospheric pressure: 630-800 mmHg

The vehicle was weighted prior to the test and than loaded up to the full weight (3500kg). Fuel consumption data (total and current flow rate) and macro-profile parameters were recorded during the drive using a Racelogic VBOX3i 100Hz. The engine ECU data (current flow rate, engine speed, vehicle speed, etc.) were taken via the CAN bus. An optical trigger was used to set timestamps at checkpoints. For ease of presentation and preparation of a photo report the drives were recorded with a dashboard camera.

The following vehicle parameters were recorded during the test:

a) Time and current position of the vehicle, including latitude, longitude, altitude and azimuth of motion;
b) Ambient pressure and temperature of the environment;
c) Speed and acceleration of the vehicle;
d) Air mass flow and its temperature at the inlet;
e) Fuel consumption (current and total from the beginning of the test drive) and temperature of the fuel in the tank;
f) Temperature of the coolant and the exhaust gases;
g) Air/fuel ratio of the mixture (both directly measured and as set by the control system).

The received vehicle parameter data log was saved the at a rate of 1 Hz. Figure 5 shows the graph of the vehicle speed based on the test drive along the route #1 - Nizhny Novgorod - Lyskovo.

Table 2 shows the final results of the test

Table 1. Technical specifications of the Gazelle Next vehicle with a Nissan TD27T engine.

Parameter	Unit	Value
Overall length	mm	5630
Wheelbase	mm	3145
Curb weight	kg	2060
Gross weight	kg	3500
Number and placement of engine cylinders	-	4, Line
Engine volume	cc	2663
Rated power at the engine speed of 4,000 min-1	hp	130
Maximum torque at the engine speed of 2000 min-1	N*m	284
Generator model	-	Hella 8EL 012 427-701
Rated power of the generator	W	1500

Table 2. Results of the test drives

Parameter	Unit	Nizhny Novgorod - Lyskovo	Lyskovo - Nizhny Novgorod	Nizhny Novgorod - Pavlovo	Pavlovo - Nizhny Novgorod
Route length	km	84.48	95.12	75.04	89.73
Average speed	km/h	67.17	59.00	43.25	48.15
Total fuel consumption	l	12.00	13.96	12.26	12.95
Average power at the crankshaft of the internal combustion engine	kW	27.9	25.1	20.53	20.1
Average temperature of the exhaust gas at the catalytic converter inlet	°C	671.50	642.08	558.38	554.59

drives, which reflect the fuel efficiency and are needed for further simulation of the vehicle fitted with the TEG.

RESULTS

Results of calculations of the thermal flows power and electric output of the TEG

Basing on the analysis of the vehicle test results we determined the most characteristic ranges of thermodynamic parameters of exhaust gas and the coolant, which allowed us to calculate the power of the thermoelectric generator for various conditions.

Location of the thermoelectric generator within the vehicle exhaust system has a significant influence on the exhaust gas temperature at the TEG inlet, so it must be fixed in advance. In this study the thermoelectric generator used in the calculations should be placed after the standard catalytic converter, so that the exhaust gas temperature drop, caused by its passage along the exhaust path and heat exchange with the environment, is 150 °C. To protect the thermoelectric generator modules from overheating and destruction the exhaust system must include a bypass channel with a regulating valve that prevents exhaust gas temperature rises above 550 °C.

Ranges of thermodynamic parameters of the exhaust gas and the coolant, used to determine the power of the thermoelectric generator, are shown in Table 3.

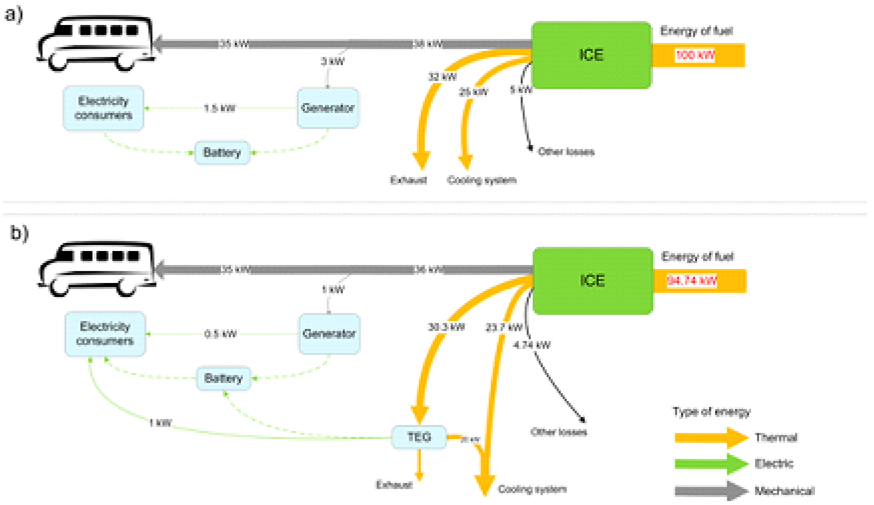
Figure 6 shows the obtained dependence of the electrical power output of the thermoelectric generator from exhaust gas and coolant temperatures at their maximum flow rates. It can be concluded from these dependencies that the efficiency of recovery of the exhaust gas thermal energy by conversion into electrical energy is better at higher mass flow rates and temperatures (which is a natural consequence of increasing the internal combustion engine capacity). Similar conclusions follow from the experimental study (Ramade et al., 2014), which presented dependencies of the TEG power output and efficiency from the crankshaft rotation speed, while the engine operated at full load.

Table 3. Ranges of thermodynamic parameters of exhaust gas and coolant

Parameter	Unit	min	max
Mass flow of exhaust gases through the TEG	g/s	10	70
Exhaust gas temperature at the TEG inlet	°C	300	560
Mass flow of coolant through the TEG	g/s	50	100
Coolant temperature at the TEG inlet	°C	60	90

Table 4. Results of calculation of the ICE fuel consumption improvement

Parameter	Unit	Nizhny Novgorod - Lyskovo	Lyskovo - Nizhny Novgorod	Nizhny Novgorod - Pavlovo	Pavlovo - Nizhny Novgorod
Total fuel consumption according to the results of the test drive	l	12.00	13.96	12.26	12.95
Average power at the crankshaft of the internal combustion engine based on the test drive results	kW	27.9	25.1	20.53	20.1
Average power spent to drive the generator according to the results of the test drive	W	1086	1020	920	966
Average TEG output	W	548.7	479.5	377.2	362.0
Average power spent to drive the generator while using the TEG	W	147	197	272	336
Reduction of power spent to drive the generator	%	86.5	82.3	37.8	65.2
Estimated total fuel consumption with TEG	l	11.61	13.50	11.92	12.53
Improvement of the ICE fuel consumption	%	3.25	3.30	2.77	3.24



a) - conventional vehicle; b) – vehicle with TEG

Fig. 1. Schemes of energy flows in the vehicle

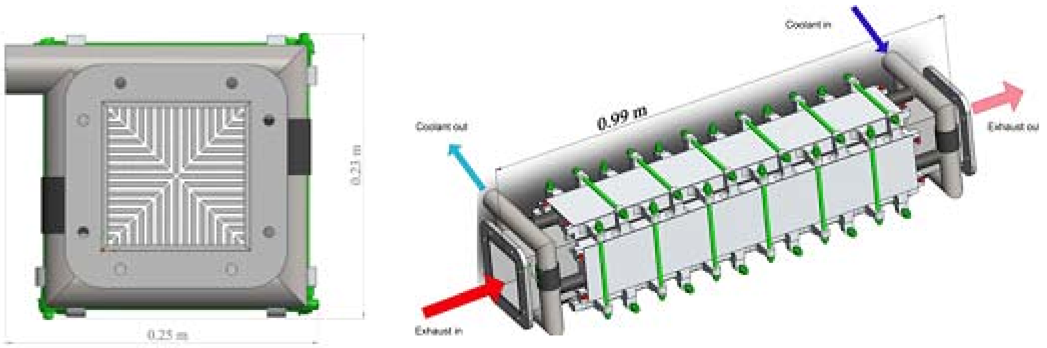


Fig. 2. Model of a thermoelectric generator for automotive internal combustion engine in solid representation

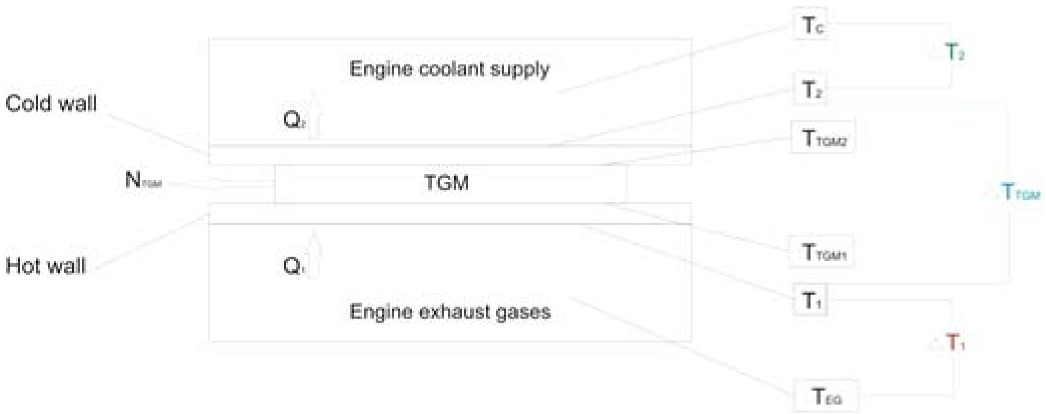


Fig. 3. Scheme of the heat transfer model of the thermoelectric generator

The above graph shows that if the exhaust gas temperature exceeds 550 °C, the theoretical capacity of the thermoelectric generator reaches more than 1kW, however, to prevent overheating of the thermoelectric generator modules, the flow of the exhaust gas through the TEG has to be limited by the regulating valve.

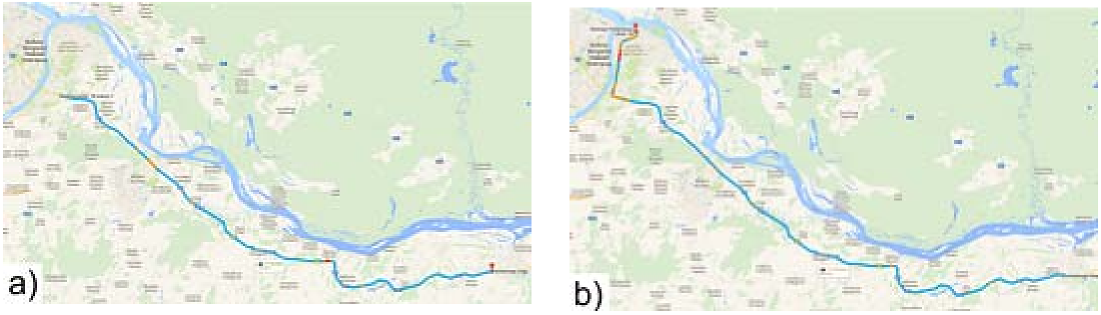
By combining the dependencies of the thermoelectric generator power on the exhaust gas and coolant temperatures at different flow rates of working fluids with the results of test drives along the specified routes we obtained graphs of the TEG electrical power output. Figure 7 shows the changes in the calculated TEG output during the drive along the route #1 Nizhny Novgorod - Lyskovo.

The data obtained allow to calculate the effect of the thermoelectric generator, manifested as a reduced level of fuel consumption by the internal combustion engine, for all the four test drives.

Results of the calculation of fuel consumption changes

Simulating the drive along the test route of a vehicle with the thermoelectric generator, which consists of routine calculation of the energy flows for each sequential moment of time and finding the current TEG power values, provided us with the values of the power required to the drive the generator. Calculations showed a significant reduction, which ranged from 37.8% to 86.5%, depending on the route. Graphs of the calculated mechanical power required to drive the generator and its changes when the TEG is used during the drive along the route #1 Nizhny Novgorod - Lyskovo are shown in Figure 8.

We also determined the external heat balance of the internal combustion engine, which is required to operate the vehicle at selected routes with constant speed and traction. On the basis of the obtained power values, included in the balance, we calculated the fuel consumption of the internal



a) Nizhny Novgorod – Lyskovo

b) Lyskovo – Nizhny Novgorod.

Fig. 4. Test routes

Fig. 5. Vehicle speed graph during the test drive along the route #1 - Nizhny Novgorod - Lyskovo

combustion engine after introduction of the thermoelectric generator and partial recovery of the heat energy. The fuel consumption improvement, expressed in liters per trip, ranged from 2.77% to 3.25%. The graphs of the measured fuel consumption during the drive along the route #1 Nizhny Novgorod - Lyskovo and the calculated fuel consumption with the TEG are shown in Figure 9.

DISCUSSION

The primary goal of this study was to evaluate the impact of a thermoelectric generator on the fuel efficiency of a vehicle during real-world operation. To this end we analyzed energy flows of a vehicle with an internal combustion engine driving the wheels, which included the cost of driving the generator. After that we developed a method to calculate the power of thermal flows and electric output of the thermoelectric generator. The obtained dependencies were used to simulate the drive of a vehicle fitted with the thermoelectric generator in its exhaust system.

The results showed an improvement of the ICE fuel consumption by about 3% after introduction of the thermoelectric generator, which is significantly less than known simulation results during the standardized driving cycles (Deng et al., 2014; Tatarinov et al., 2013). It can be explained by irregular and powerful accelerations of the vehicle during the test drives and other factors, not accounted for in the test procedures following the standardized driving cycles.

We should also point out that the power generated by the thermoelectric generator (up to 1kW) is not sufficient to provide electricity to the on-board network of the vehicle, hence the use of a similar but more powerful TEG can further improve fuel consumption.

In the future, to determine the most

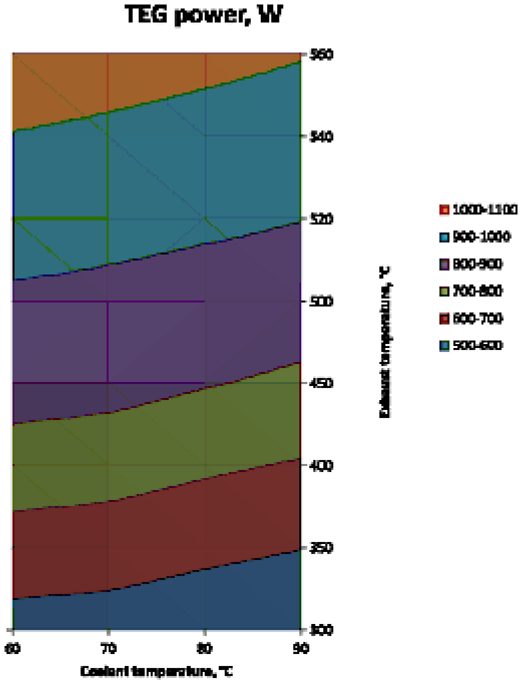


Fig. 6. Graph of the TEG power output dependency from exhaust gas and coolant temperatures

Fig. 7. Graph of the calculated TEG output during the drive along the route #1 Nizhny Novgorod - Lyskovo

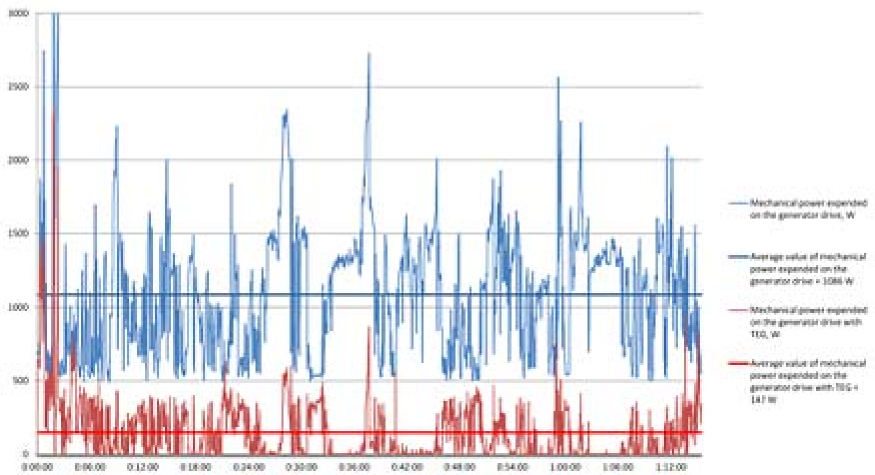


Fig. 8. Graphs of calculated mechanical power required to drive the generator and its change when the TEG is used during the drive along the route #1 Nizhny Novgorod - Lyskovo

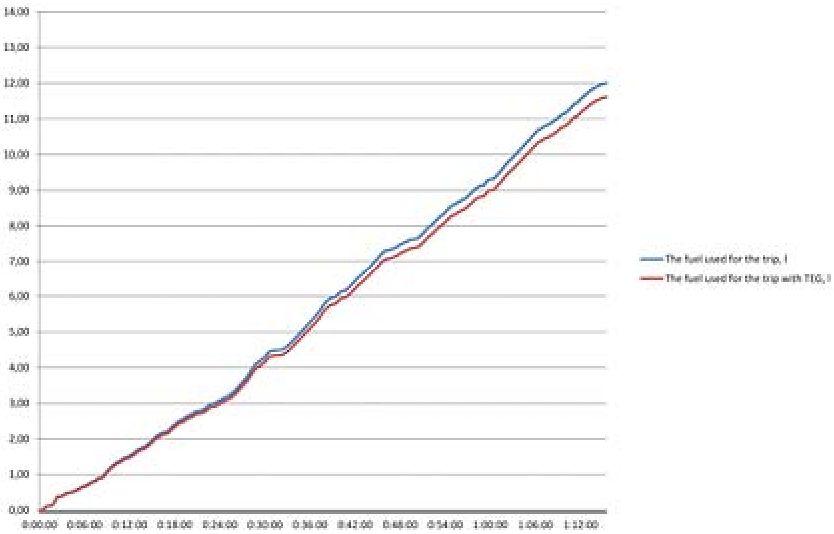


Fig. 9. Graphs of the measured fuel consumption during the drive along the route #1 Nizhny Novgorod - Lyskovo and calculated fuel consumption with the TEG

efficient applications of thermoelectric generators, which recover thermal energy of ICE exhaust gases, it is advisable to do similar studies of fuel consumption using vehicles equipped with spark-ignition and hybrid engines.

CONCLUSION

The studies resulted in numerical data describing the influence of a thermoelectric generator in a vehicle with an internal combustion engine driving the wheels on fuel efficiency, taking into account real-world experience. For the sake of the research we performed test drives of a light commercial vehicle "Gazelle Next" with a TD27T engine along several routes spanning regional roads of the Nizhny Novgorod region, primarily with suburban traffic.

Calculations were carried out according to the developed method on the basis of the tests that involved registration of not only the basic vehicle and engine parameters, but also thermodynamic parameters of the exhaust gas and coolant. The results were used to calculate the electric output of the TEG at each moment of time, which allows to evaluate its effect on the fuel economy of the vehicle as a whole.

Analysis of simulation results brings the following conclusions:

a) Optimized finning of the thermoelectric generator body with variable fin height and groove width provide a TEG electric power output reaching 1 kW at the exhaust gas temperature of about 500 °C and the mass flow rate of about 35 g/s;
b) The fuel consumption improvement, expressed in liters per trip, ranged from 2.77% to 3.25%, depending on the route;
c) Use of a similar but more powerful TEG can further improve fuel consumption while keeping the operating temperatures of the thermoelectric generator modules within normal range.

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