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# INVESTIGATION OF WASTE HEAT RECOVERY FOR AUTOMOBILE APPLICATION BASED ON A THERMOELECTRIC MODULE

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***Abstract***

*The article presents a brief discussion about issues of energy harvesting of waste heat generated during the operation of the SI (spark ignition) internal combustion engine (ICE). The available methods of implementation and the problems associated with them were presented. In recent years, there has been an increase in the significance of successful researches on new types of thermoelectric modules. Despite relatively low efficiency of the thermoelectric modules, a systematic growth in their interest is observed. Their application seems to be reasonable because of many advantages - mainly the simplicity. The paper contains the literature review in the subject of interest. For the purpose of this work, a test rig was designed and manufactured. The test rig consists of a single thermoelectric module and makes it possible to work in variety of operating conditions for different values of the exhaust gas flow rate and temperature. It is equipped with an automatic, servo controlled, movable element, which control direction of the exhaust gas flow and as a result changes the heat flux transferred via the thermoelectric module. This solution allows achieving the maximum power of the thermoelectric module in a wide range of ICE operating conditions and also allows adjusting operating parameters to actual working conditions of the whole system. The problems encountered during the construction of the test rig and the proposed solutions of practical implementation were described. Experimental research was conducted on a small size automobile petrol engine. The influence of electrical parameters at the output on the whole system was analysed. The results suggest that the actual thermoelectric module parameters, especially the thermal conductivity, vary from declared by the producer. Maximum achieved electric power output reached about 10 W from a single thermoelectric module (57 mm x 54 mm), which is nearly half of the declared value.*

***Keywords:*** *energy harvesting, combustion engine, heat recovery, exhaust gas, thermoelectric effect*

## 1. Introduction

According to constantly growing requirements imposed on automotive vehicles, concerning emission of harmful substances, noise, nuisance to the environment, fuel consumption and operating costs, it is necessary to search for new and developing the known methods of improving their construction. ICEs used today achieve maximum mechanical efficiency of about 35% for SI engines and about 45% for Diesel (CI) engines used in cars. The rest of the energy supplied to the engine as a fuel, in conventional approach is waste [2].

Most energy incorporates the exhaust gas leaving the combustion chamber. Their enthalpy can be partly used, for example in a turbocharger. However, the largest energy flux is related to the temperature of the exhaust gas, which is discharged. Currently, many researches related to recovery of waste energy are carried out. It is predicted that significance and the speed of development of such research will increase [5, 7, 17].

These studies relate, among the others, to the application of independent operating system based on a Rankine cycle, where the heat source is a stream of exhaust gas [3]. The power generated in this system can be converted into electric power or mechanically added directly to the drive shaft of the ICE. Such a system can however, cause many technological problems due to its complexity and the presence of water or another circulating medium (Organic Rankine Cycle). Energy can also be recovered by water injection into the exhaust manifold [24], where the evaporation causes an increase in volumetric flow inside the exhaust system resulting in power growth of installed turbine (e.g. Turbocharger). Another way to use the waste heat of the exhaust gas is a system based on the thermoelectric effect. Occurring phenomena is called Seebeck effect, which is based on generation of electromotive force in a circuit composed of different types of conductors when their connections are disposed at different temperatures. This is related to differences in energy of passing electrons, which forms electric current. The principle of operation of such devices is described in detail in many publications [6, 9]. Currently, the thermoelectric modules are available commercially, designed for generating electric current with a heat flux flowing through. Most of them is designed for operation at low temperatures (<100°C), but more advanced models can operate at temperatures up to hundreds degrees Celsius. Application of these devices for the recovery of heat generated during the ICE operation appears to be perspective [7, 18]. The advantages of such a system include simple structure, in comparison to other heat recovery installations (no moving parts, except the auxiliary equipment), maintenance-free and durability. In the case of using thermoelectric modules it should be noted that the operation parameters for highest efficiency are not identical with those of maximum output electric power [23]. There is a possibility of building different systems due to the manner of collecting heat flux and its source. One way is to use an engine liquid cooling system, by complete or partial replacement of conventional cooler [2]. It is also possible to use the exhaust gas recirculated to the combustion chamber (EGR) [4], but this solution modifies working conditions and methods for engine operation control. The most obvious solution is to use the heat contained in the exhaust gas [14, 18, 20]. The main disadvantage is the low efficiency of thermoelectric modules interpreted as the maximum electric power obtained at the output (by the proper choice of the resistance of power receiver) to the supplied heat flux. The modules available on the market are characterized by several percent efficiency [16, 18], which is a small fraction of the theoretical limitations of the second law of thermodynamics.

Another disadvantage is the technical difficulty of ensuring a large temperature difference between cold and hot side of the thermoelectric module. This issue is due to the small thickness of the module (a few millimetres) and if the thermoelectric module is considered as a homogeneous part, it has a relatively high thermal conductivity. This provides fairly large heat flux, but naturally, it impedes to maintain the desired temperature gradient. For this reason, it is required to provide extensive cooling at cold side with air or liquid. Literature describes also use of heat pipes [13]. Possible applicable solution is to connect in series the thermoelectric elements due to the flow of heat, and then the cold side of one module is connected to the hot side of the next one.

Extremely important topic is to design the geometry of the flow channel to obtain sufficiently intensive heat exchange. An impact of additional elements that modify the flow is described in [11, 15, 19]. Increasing the efficiency of the engine by the use of thermoelectric modules leads also to a reduction in pollutants emission of a vehicle. Publication [1] considers an impact of heat recovery on $CO_2$ emissions during the NEDC test. An important issue is the selection of modules quantity and the power consumed by them to the desired engine configuration. An obvious limitation is the amount of energy contained in the exhaust gas associated with temperature excess above the ambient temperature. The study [22] presents a situation when not covering all available exchange surface by thermoelectric modules turned out to be more profitable. This resulted from the increase of the hot side temperature of remaining cells. The energy obtained from exhaust gas heat can be then used to charge the battery, power ignition system and electrical system of the car. Crucial element after starting the engine is the time, when the parameters of the generated electricity reach desired values, e.g. ability to self-power the ignition system and main the controller.

A crucial issue is to ensure a proper thermal contact in the structure of the entire device, among others, contact pressure between elements [12]. Position of the recovery module relative to other elements of the exhaust system should be also considered [10], especially the three-way catalytic converter and other exhaust gas treatment devices need proper temperature for operation. Installing into the exhaust system some additional components changes the pumping resistance, especially in the case of multiple modules, as well as intensification of the heat flow through intensive turbulence of exhaust gas [8].

This paper concerns determination of selected operating parameters of the tested thermoelectric module in the proposed system configurations.

## 2. Test rig

Test rig for the experimental determination of the operating parameters of the thermoelectric module was built. Its main component is the small capacity (899 cm$^3$) automobile SI engine. This unit is equipped with a single-point fuel injection. Maximum power and torque are 39 hp at 5500 rpm and 65 Nm at 3000 rpm, respectively. Eddy current brake was used as an engine load.

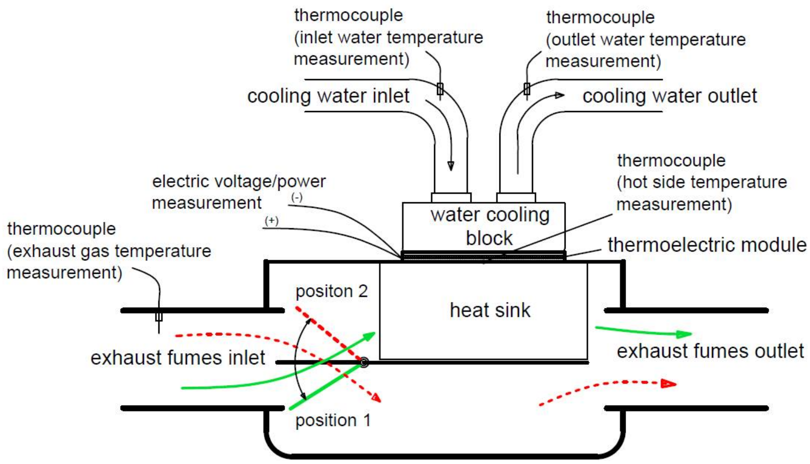


*Fig. 1. Device scheme*

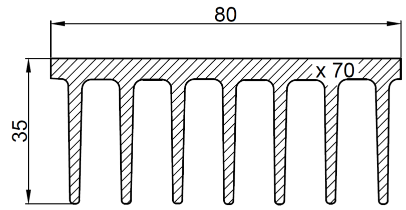


*Fig. 2. Heat sink profile*

In the exhaust layout of this engine the thermoelectric system shown schematically in Fig. 1, was installed. It consists of a box and an aluminium radiator with dimensions 80x70x35 mm placed inside, whose profile is shown in Fig. 2. Diameter of pipes is 35 mm. A crucial element inside is a movable plate (flap), which allows to control the flow rate of exhaust gas. Position of the flap is adjusted with a servomechanism. The system was mounted at the exhaust pipe at the distance of about 30 cm from the exhaust manifold, where originally a three-way catalytic converter was located. K type thermocouples were used to measure temperatures. The flue gas temperature was measured before the test device (at the box inlet). One of the box wall is attached with screws and can easily be removed. The hot side of the thermoelectric module contacts with the heat sink placed in exhaust gas stream, whereas the cold side is water-cooled by a copper block, designed to cool the high-performance CPUs. To fill the connections a thermal grease was used. The main element of the energy recovery system is a thermoelectric module manufactured by European Thermodynamics Ltd., designation GM250-449-10-12 [21]. Provided technical data are shown in Tab. 1.

*Tab. 1. Thermoelectric module technical specification*

| | | | |
|---|---|---|---|
| Matched load output power | 22.3W | Matched load output voltage | 14.75V |
| Matched load resistance | 9.76Ω ± 15% | Heat flaw through module | ~446W |
| Open circuit voltage | 29.5V | Maximum compress | 1MPa |
| Matched load output | 1.51A | Maximum operation temp. | Hot/Cold side 250/175°C |

To achieve maximum power the cold side temperature should be maintained at 30°C. Tap water at a temperature of about 16-18 °C was used for cooling. Due to the high cooling capacity of the water block, an assumption that the temperature at the junction of thermoelectric module is 30°C was made, during all the measurements. For maximum power of the module, temperature of the hot side should be equal to the maximum allowable temperature, therefore 250°C. The exhaust gas was much hotter than the heat sink, and therefore there was a large temperature difference, which can be used to shape the heat flow. At the cold side temperature, difference was much smaller, so the connection was found to be crucial for the desirable operation of the entire system. Hence, a thermal grease with higher thermal conductivity (and lower resistance to high temperatures) was used. The proper contact between the surfaces was maintained.

An electronic circuit for automatic control of the flap position was designed and built. The main element was a microprocessor Atmel AVR that uses analogue-to-digital converter for reading the input voltage (output voltage of a thermoelectric module). The designated voltage characteristics versus the temperature of the module hot side were used to determine the limit voltage values for which the flap should be moved. This method was valid for fixed resistance values of the receiver. In this way, proper operation of the system was achieved. Another issue was the energy needed to ensure a continuous flow of coolant through the cooling block, which was not included in the discussion. Coolant flow during all of the measurements was about 0.85 l/min, which in each measurement gave liquid temperature rise of less than 6°C.

## 3. Experimental results

For proposed configuration of the test rig the measurements during cold start for idle operation were made. The rotational speed was set to 1200 rpm, without load. The flap was set to the position that intensifies heat transfer. Fig. 3 presents the module hot side temperature, exhaust gas temperature and open circuit voltage of the module versus time from start. After 900 s a steady state was achieved.

Figure 4 shows the exhaust gas temperature and exhaust stream versus torque for 1500 rpm in steady state. The stream was calculated using fuel consumption measurement and known engine air ratio.

Figure 5 shows the temperature of the hot side of the module in the steady state and the transferred heat flux. The measurements were performed for 1500 rpm in two series, the first for an open electrical circuit cell and the other for short circuit. For the torque 20 Nm and lower, the flap was in the position that intensifying the heat flux. For load 30 Nm and higher it was in the opposite position. It can be seen that using the proposed solution, combined with the correct positioning of the flap, the maximum operating parameters of the module (limited by a maximum temperature of the hot side) can be achieved for the torque range of 20-45 Nm. Such a result was obtained with an electronic system described above.

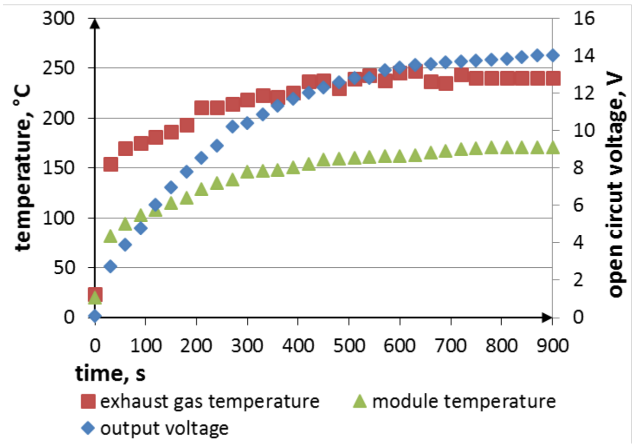


*Fig. 3. Parameters during start-up*

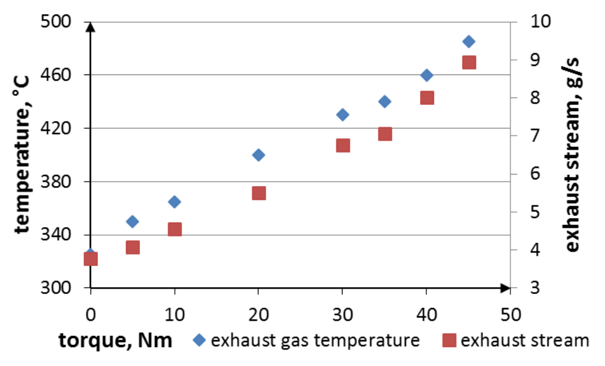


*Fig. 4. Exhaust gas temperature and stream at 1500 rpm*

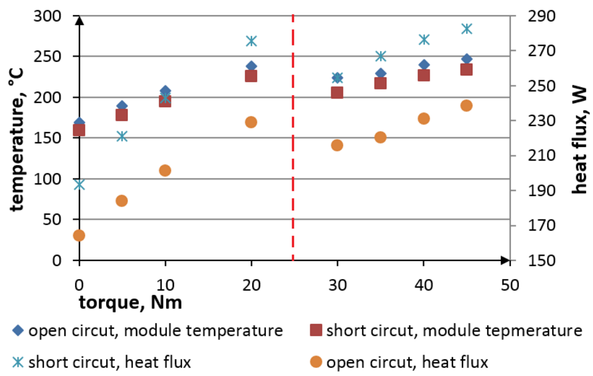


*Fig. 5. Thermoelectric module hot side temperature and heat flux at different electric conditions (1500 rpm)*

For several selected operating conditions of the engine, measurements using different values of the power receiver electrical resistance were made. They showed (with fairly good accuracy) a linear dependence of the voltage generated by a thermoelectric module versus current in the circuit. Accordingly, it was assumed that the maximum power could be determined from open circuit voltage and short circuit current.

With the increase of the current in the circuit, the amount of heat absorbed by the module also increases. Part of the energy delivered as heat is transferred into electric power, but the increase in the heat flux is much greater than that resulting from the sum of the electrical energy and the open circuit operation heat flux. The source of a significant change in the thermal conductivity is probably the Peltier effect and Joule heat caused by electrical current flow. Increased heat flux, for constant operating parameters of combustion engine, leads to reduction in temperature of the hot side. Based on the collected data, it can be assumed that the Thompson effect had a marginal importance. The scope of these changes is visible from the data presented in Fig. 5. The maximum attainable electric power and open circuit voltage of the thermoelectric module is presented in Fig. 6.

Subsequently measurements at an engine speed 2000 rpm were performed. For this value, two series of measurements without load (0 Nm) were conducted, at two extreme position of the flap. Measurements with other load values were carried out with the flap in a position maximally reducing the heat flux. When using the dynamically controlled flap it is possible to achieve the maximum thermoelectric module operating parameters for the range 0-30 Nm at this rotational speed. Fig. 7, 8 and 9 present the measured values for speed 2000 rpm in the same way as above for 1500 rpm.

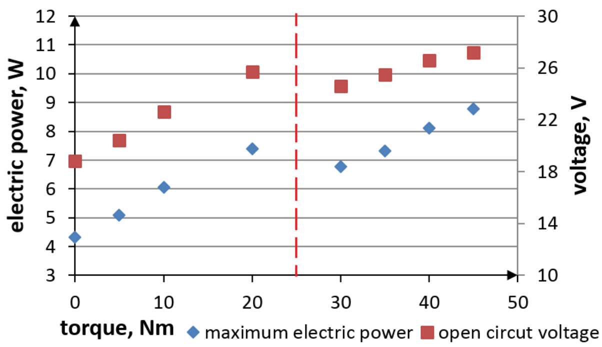


*Fig. 6. Electric output parameters (1500 rpm)*

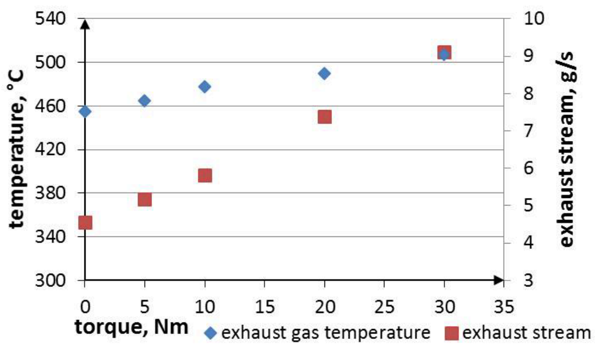


*Fig. 7. Exhaust gas temperature and stream at 2000 rpm*

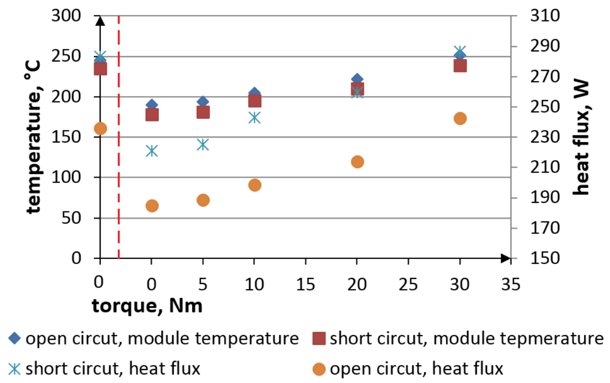


*Fig. 8. Thermoelectric module hot side temperature and heat flux at different electric conditions (2000 rpm)*

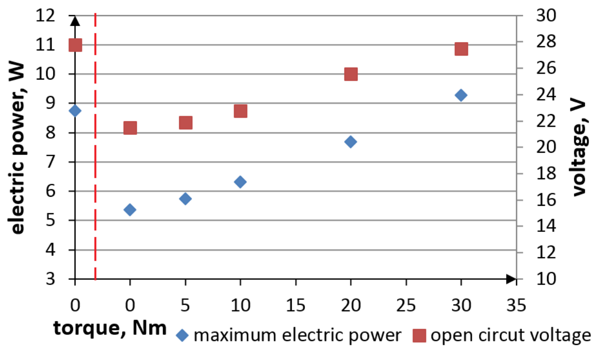


*Fig. 9. Electric output parameters (2000 rpm)*

The collected data show that the module working in conditions close to the design ones (250°C and 30°C) conducts less heat than according to data provided by the manufacturer (Tab. 1). During the conducted experiments, the temperature of the thermal grease constituting the contact layer with the surface of the heat sink was measured, rather than true temperature of the module. However, this value can be taken as the module surface temperature, as confirmed by the characteristics provided by the manufacturer for the open circuit voltage versus hot side temperature. The resulting voltage measurements exhibit only a slight discrepancy from it. During electrical load variations of the module the heat flux does not change drastically, so it can be assumed that (similar as for the open circuit measurements), thermal resistance of the thermal grease layer has a negligible effect on the operation of the system. The maximum measured power value is approximately half of this specified by the manufacturer.

## 4. Conclusions

Within this work, the measurements for the proposed configuration of the experimental system were made. The parameters of the tested thermoelectric module differed, in proposed configuration, from those declared by the manufacturer. If the heat flux passing through the module would be larger, heat sink temperature would be lower, which would allow the system to operate at higher engine speed and power. The proposed geometry, which includes a control flap, increased the range of parameters of the engine operation for which it is possible to achieve maximum performance without destroying the module. The efficiency of the thermoelectric module, understood as a ratio of maximum achievable electric power to the average heat supplied, was in a range of 2.4-3.5%. For the design of the system consisting of a greater number of cells to be used in a motor vehicle, further studies taking into account the changing parameters of exhaust gases should be conducted.

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