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The potential of thermoelectric energy harvesting in vehicles equipped with ICE

The paper deals with an issue of waste heat recovery in a selected configuration of an internal combustion engine. A possibility of using thermoelectric cells (currently available on the market) for production of electricity with heat extracted from the exhaust gas was considered. The calculations were made using specialized software. Features and design assumptions of the heat recovery system were presented and their influence on parameters of the entire system was investigated (efficiency of the internal combustion engine, power, etc.). An assessment of the applicability of the energy recovery system based on thermoelectric effects and characteristic of the proposed configuration was performed. Some issues that require further research have been highlighted.

Key words: *combustion engine, heat recovery, thermoelectric module, heat transfer, exhaust system*

1. Introduction

Improvement in internal combustion engine performance is one of the main goals engineers deal with. There are many sophisticated solutions based, in some sense, on controlling the combustion process inside the combustion chamber and the piston motion. Some of them increase pressure, temperature, compression ratio, valve timing, etc. But in nearly every combustion engine system a significant part of the energy is lost due to the waste heat expelled to the surroundings [10]. Some heat is lost in the engine cooling system, via the central radiator, but this heat source has relatively low temperature. Much higher temperature occurs, however in the exhaust system. An attempt was made to analyse the possibilities, issues and selected problems of heat recovery from the exhaust gas. One of the possibilities discussed in this paper is the use of the thermoelectric modules, which convert heat into electricity. The basic principle of their operation is the Seebeck effect. A thermoelectric module is usually a flat sheet (thickness of a few millimetres) of semiconductors between ceramic (electrical insulator) plates. If a thermal gradient occurs throughout the module a voltage difference is generated [3, 9]. The thermoelectric modules have several advantages like the lack of moving parts, long lifetime, very small size and noiseless operation. On the other hand, their efficiency is rather low. There are, of course, some more efficient methods of waste heat recovery (Organic Rankine Cycle, turbine) but they are usually quite complex and difficult or unreasonable to use in mobile applications [4, 14]. The thermoelectric module can be easily retrofitted, e.g. by replacing genuine muffler with a modified one. Descriptions of experimental research systems, including modules assembled into vehicles can be found in the literature [2, 7, 11]. The following considerations were performed to make a coarse assessment of the amount of heat which can be recovered, overall characteristics of such heat recovery system and different working conditions that can occur in typical vehicle drivetrain. The result obtained can be useful in a design process of specific heat exchangers, identifying crucial issues and targets.

2. Modelling approach

The analysis of waste heat recovery was based on a 4 stroke, a spark ignited, 500 ccm motorcycle engine. A simplified model of immediate fuel combustion at a constant volume was used. Perfectly stoichiometric air to fuel ratio was assumed and friction inside the engine block between moving elements was neglected. The exhaust system in proposed configuration consists of, among the others, a thermoelectric module assembly unit. This assembly consist of a straight pipe, in which exhaust gases flow, a highly heat conductive material between inner pipe surface and the thermoelectric cells (hot side heat exchanger – heat source), the thermoelectric module and the cooling system. The hot side of the thermoelectric module can be attached directly to the heat source (a flat surface covered with thermal grease). The opposite side of the thermoelectric module should be attached to the water cooling system (cold side heat exchanger – heat sink). The remaining surfaces were assumed adiabatic. Figs 1 and 2 present both a cross-sectional and an isometric view of the heat recovery system proposed.

The specialized software – AVL Boost, was used to carry out the simulations.

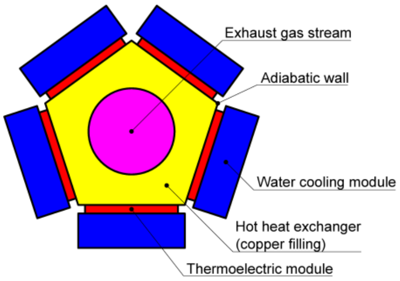

Fig. 1. A cross-sectional view of thermoelectric module assembly

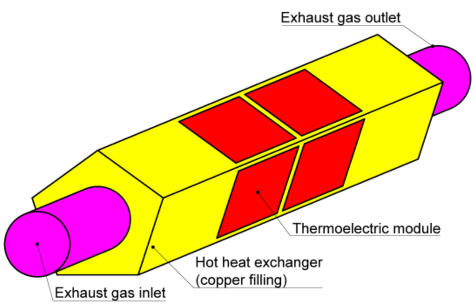

Fig. 2. Thermoelectric module assembly

The overall thermal resistance of this assembly can be calculated as the proportionality factor between heat transferred through the system (from the exhaust gas to cooling water) and temperature difference at both sides of the domain. One of them is the inner surface in contact with hot exhaust gas, whereas the second one is the thermoelectric module cold side (cooled with water flow from the cooling system). Due to a major difference in magnitudes of thermal resistance of the thermoelectric module and the heat exchangers the heat exchangers resistance can be neglected [1]. In other words, if constant heat flux is imposed to the system the temperature gradient is significant only across the thermoelectric module whereas within the hot heat exchanger the temperature distribution is nearly uniform. The same situation occurs at the cold side – the temperature of the heat exchanger and the module cold side is almost the same. This assumption is true for heat exchangers made of a highly heat-conductive material, e.g. copper. In such a case, the gas-wall temperature difference drop along the flow direction is not large. In the described configuration it is relatively small (not greater than 100 K), so the temperature of heat source for modules in one thermoelectric assembly was assumed to be constant. As a result, in one assembly the temperature of the inner wall (in contact with exhaust gases) and thermoelectric modules hot side is the same [1, 6].

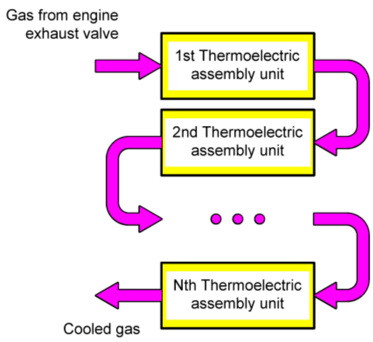

Fig. 3. General configuration of exhaust heat recovery system

Based on literature and the technical data of commercially available thermoelectric modules, the thermal conductivity of exemplary module (Tecteg TEG1-PB12690) was assumed as about 0.5 W/K (~ 273 W/570°C) for surface 62 mm × 62 mm [12] (0.5 W/K corresponds to 2 K/W thermal resistance). Thermal conductivity of the thermoelectric module is subjected to change with electrical load (electric current in a circuit results with the Peltier effect – phenomena related to the Seebeck effect). However, using a DC/DC converter within the system, whose aim is to provide optimal working conditions (electrical resistance of power receiver for the highest module power or the highest efficiency) immediately minimises the problem. So, the overall thermal conductivity can be assumed constant [1]. Proposed thermoelectric assembly unit consists of 10 mentioned thermoelectric modules attached to the exhaust pipe. The modules used have a maximum allowable working temperature of 600°C. To keep the constant temperature distribution within the heat source, the modules should be uniformly distributed on the heat source surface, e.g. if the cross section is pentagon-like showed on Fig. 1 it results in 2 thermoelectric modules (62 mm × 62 mm) on each wall. The temperature of the heat source was determined based on the 0.5 W/K thermal conductivity of the thermoelectric modules. For 10 thermoelectric modules (one assembly unit) the thermal conductivity (reverse of thermal resistance) is about 10 W/K. On this basis, a script in C language was developed and implemented in the software to calculate the temperature of the heat source. The module cold side temperature (resulting from water cooling) was assumed to be 50°C. To model the heat transfer coefficient between the stream of exhaust gas and the channel wall (heat source, with a temperature equal to module hot side) a Reynolds analogy have been used. It provides a rough approximation of a general heat exchanger. The amount of electric energy produced as useful result in thermoelectric module was calculated using the heat transferred from exhaust gas into the heat exchanger in assembly unit (heat recovered in a unit) multiplied by temperature gradient between hot and cold side of the thermoelectric module and then multiplied by factor (0.000128) corresponding to the datasheet of the thermoelectric module (~7% efficiency at 600°C/50°C). The efficiency of electric power generation can be assumed proportional to the temperature gradient, so it is adopted here.

An alternative method for efficiency assessment can be based on Carnot efficiency for given temperatures (heat source and heat sink) multiplied by an appropriate factor. This method corresponds to the assumption that the thermoelectric figure of merit (coefficient of performance) is constant over temperature for the thermoelectric module component materials (semiconductors, legs) [9].

3. Reference experimental setup

At the initial step of considerations, to avoid an influence of intensive wave phenomena, a large plenum (500 litres) have been added between the exhaust port and the thermoelectric module assembly(s). It was assumed adiabatic, so temperature and enthalpy changes were negligibly small. Its only task to stabilize the exhaust gas velocity to obtain reference data without the influence of pressure waves and cyclic motions. The plenum is connected with exhaust port via adiabatic, 31 mm – diameter and 500 mm – long pipe. The pressure waves within the pipe influence to some extent the exhaust gas discharge, but these phenomena are not analysed here. Dimensions of this pipe were chosen to reduce the unavoidable effects as much as possible. The variations in velocity due to the plenum over one engine cycle do not exceed 3%. Without the plenum, the changes are, not only bigger than 100%, but also a backflow is observed. So, the use of plenum justifies the assumption of a constant velocity flow. A total number of nine thermoelectric assembly units were simulated. Figure 3 presents the overall view of the AVL Boost model. These units are represented by pipe 8 and 10–17 (marked in red in Fig. 3). Restrictors between them are dummy elements with coefficients "1". The formula interpreters calculate wall temperatures for thermoelectric assembly unit (one pipe means one unit, each of the nine units is equivalent of 10 thermoelectric modules). All simulations were made to represent only the steady-state conditions and the calculations were conducted to achieve the convergence with the spatial resolution of 10 mm.

The heat flux throughout the assembly can be adjusted, within the software, with the heat transfer factor parameter. It is a ratio of real heat transfer coefficient and the value used in calculations. A value equal to one represents conduction in the simple pipe, as shown in Fig. 1. Values greater than 1 represent e.g. internally finned pipe or other changes in geometry which intensify the heat flow. This value was set to keep the maximum temperature at the allowable limit (exceeding 600°C of pipe wall temperature would damage the module). This condition results in heat transfer factor of 1.02. Particular solutions of heat exchangers for thermoelectric modules to provide the best heat exchange can be found in the literature [5, 8].

The calculations were made for a reference point - full throttle, 6000 rpm. The mechanical power of the engine is therefore 24.62 kW. Total enthalpy flow behind the plenum is 27.7 kW (reference zero: 1 atm; 25°C), which corresponds to temperature 1278 K, mass flow 24 g/s and velocity (mean) 69 m/s. Table 1 shows some selected results obtained for the thermoelectric module assembly units. Heat flux means heat recovered in particular assembly unit (heat flux through thermoelectric modules), electric power is generated by thermoelectric modules as described above, and it is the useful effect.

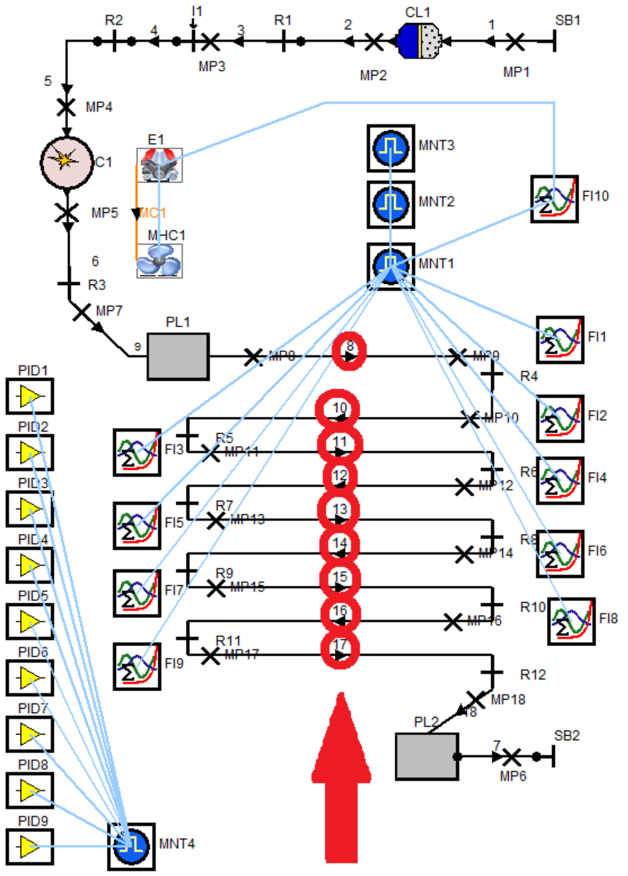

Fig. 4. Overall view of test bench in AVL Boost

It can be seen from Table 1, that efficiency of each next thermoelectric assembly unit decreases. This results from a reduction in the temperature of the exhaust gas which, in consequence, decreases the heat flux and efficiency of the thermoelectric modules due to a drop of temperature gradient.

Table 1. Selected parameters of nine units (heat transfer factor for every unit – 1.02) during operation in full throttle at 6000 rpm

Thermoelectric assembly unit	Inlet gas temp. [K]	Outlet gas temp. [K]	Wall temp. [K]	Heat flux [W]	Electric power [W]
1	1278	1191	873	2748	193
2	1191	1111	820	2483	158
3	1111	1038	771	2242	129
4	1038	972	728	2023	105
5	972	910	688	1823	85
6	910	855	651	1642	69
7	855	804	651	1478	56
8	804	758	589	1330	45
9	758	716	562	1196	37
Sum				16966	877

Table 2. Selected parameters of nine units for variable heat transfer factor during operation in full throttle at 6000 rpm

Thermo-electric assem-bly unit	Inlet gas temp. [K]	Outlet gas temp. [K]	Wall temp. [K]	Heat flux [W]	Elec-tric power [W]	Heat transfer factor [-]
1	1278	1191	873	2751	194	1.02
2	1191	1102	873	2751	194	1.38
3	1102	1013	873	2751	194	2.10
4	1013	921	873	2751	194	4.49
5	921	836	827	2520	163	10
6	836	761	754	2154	119	10
7	761	697	754	1836	101	10
8	697	641	635	1561	62	10
9	641	593	588	1325	45	10
Sum				20400	1265	

In the next step, a PID regulator has been involved in the system and tuned to set the heat transfer factor for every thermoelectric module assembly independently. Obtained data are presented in Table 2.

As it can be noticed from Table 2, the total recovered energy in the form of electric power is about 1.27 kW. To provide the same heat flux, and in consequence, the same temperature of the module, greater heat transfer factors are required. This is because of the drop in enthalpy of the exhaust stream. Here, the heat transfer factor was arbitrarily limited to 10.

In the next stage, the plenum has been modified. Its volume changed from 500 l to 5 l. The variation of velocity during one engine cycle is now significant. Values of instantaneous velocity behind the plenum are in this case between 110 m/s forward and 10 m/s reverse. For this situation, similar analyses were made as described previously and presented in Table 2. The mean inlet and outlet gas temperatures are the same as before. For the first four thermoelectric module assemblies, the wall temperatures also must be the same because it is a criterion to tune the heat transfer coefficient and it is equal to the maximum allowable thermoelectric module temperature.

Table 3. Optimal heat transfer coefficient for each first four subsequent thermoelectric module assembly

Thermoelectric assembly unit	1	2	3	4
Heat Transfer Coefficient	1.06	1.44	2.26	5.34

Because of the amount of energy and reasonably small heat transfer factor, further considerations are limited to four thermoelectric module assemblies. The heat transfer factors are also similar. Table 3 presents the heat transfer coefficients for the 5 l plenum.

4. Experimental setup in different working conditions

For further considerations, the system consisting of four thermoelectric module assemblies (each assembly consists of 10 modules) were taken into account. Each of them has different heat transfer factor coefficient presented in Table 3, which is optimum for the reference point (6000 rpm, full throttle). The proposed system was analysed at different working conditions.

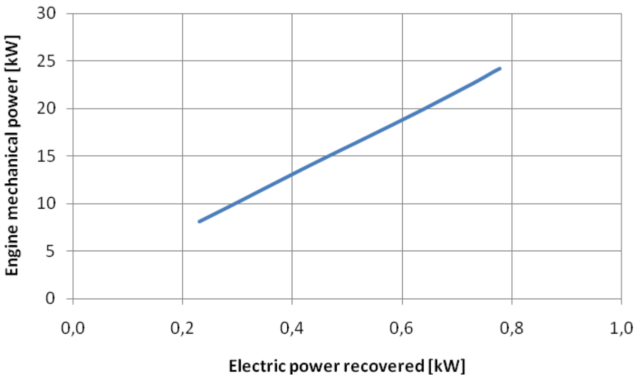

Fig. 5. Recovered power for 6000 rpm

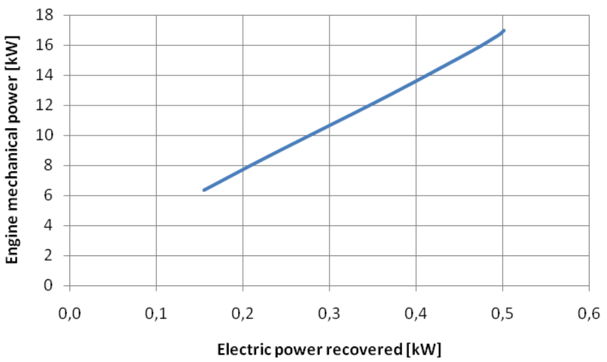

Fig. 6. Recovered power for 4000 rpm

Two rotational speeds of 6000 rpm and 4000 rpm were considered, with different throttle position, from 5% (flow coefficient restriction 0.05 in the intake manifold) to 100% (flow coeff. 0.98). Diagrams in Fig. 5 and Fig. 6 show the total amount of harvested electric energy in the four thermoelectric module assembly (40 thermoelectric modules in total).

5. Results discussion

The results of the proposed configuration have been presented above. In the first configuration, when nine thermoelectric module assemblies are identical, the recovered electric power was 877 W. It is about 3.5% of the engine mechanical output power. After modification of the thermoelectric module assembly assuming individual tuning of geometry (heat transfer factor) for every unit, the efficiency of more than 5% was achieved. But for units number 5 to 9 a high heat transfer factor is necessary. This value has been limited to 10 in this paper due to practical reasons. The highest possible amount of produced electric energy is achievable only in the first four units. The efficiency of the thermoelectric module becomes lower as the temperature of the heat source decreases. The influence of cyclic motion and pressure wave is relatively small in this case. It is hard to predict how this phenomenon influences the whole system. On one hand, the forward and reverse cyclic motion intensify the heat transfer factor, but on the other, some portion of the hot gases can be rapidly pushed through the heat exchanger. Some description and analysis of this phenomena can be found in [13]. The behaviour of the proposed system is nearly linear with decreasing load of the engine for both investigated rotational speeds.

6. Conclusion

Results obtained in the investigation can be useful for further analysis concerning the geometry of heat exchanger, economic profitability of waste heat recovery systems. It can also be helpful in rough estimation of the number of thermoelectric assemblies or simple modules. The geometry was assumed arbitrary. In the real arrangement, this can vary significantly and influence heat transfer phenomena due to cyclic pulsation in the exhaust system. It can enhance or lower the effective heat flux. The length of the heat exchanger can also have a different influence depending on the engine rotational speed and a ratio between gas pulse length and heat exchanger length. Some ways of enhancing the heat flux are the elongation of the heat exchanger, internal fins, turbulisers, etc. It has to be a subject of further investigation which one is more profitable. The acoustic phenomena have not been taken into account in this case and further investigation dealing with sound level and exhaust after treatment (3 W cat, DPF) should be also performed. The amount of energy possible to recover is not very large, Although it should be notified, that this is the electric energy – with high exergy level. In conventional solutions, the alternator is used to produce electricity and its efficiency, the amount of consumed mechanical power have to be also considered. In the pro-posed configuration, the power of alternator changes, it can possibly be switched off or working like an engine. The transient phenomena and heating period have to be also the subject of further investigation. Reasonability of using the thermoelectric solution strongly depends on the development of thermoelectric cells, materials and their cost.

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