TECHNOLOGIES OF USING ENERGY HARVESTING SYSTEMS IN MOTOR VEHICLES – ENERGY FROM EXHAUST SYSTEM

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Abstract. The energy demand in the automotive sector is significant and fuel and vehicle maintenance costs constitute a significant part of road transport expenditure. Over the past few decades, there has been a great interest in various types of alternative fuels and the production of economical internal combustion engines. The development in this sector is dictated by the greater interest of producers in the protection of the natural environment, which is visible and enforced by legislation in the form of stricter emission standards. For these reasons, more and more often systems are sought that will save energy and cause less losses in the so-called wasted energy which is dissipated. The efficiency of modern combustion engines is about 40%, the rest of the energy is lost. As a result, the search continues for systems that will use this part of energy to power certain systems or micro-sensors in the vehicle. This study presents energy recovery systems in motor vehicles, the interest of which has increased in the last decade. The attention was paid to the changes taking place in the automotive industry, current development trends and directions of academic research. The possibilities of energy recovery from such vehicle systems as energy recovered during braking, damping energy in the vehicle suspension from vibrations of the internal combustion engine with particular emphasis on energy recovery from the exhaust system of the internal combustion engine were presented. Based on the literature study of the presented research of various research centres, it can be concluded that there is a huge potential in the harvesting of loss of thermal energy. It is possible to recover thermal energy from approx. 100 W for passenger cars to over 800 W for large diesel engines in trucks. Globally, energy recovery systems can be used in modern vehicles powered by internal combustion engines, but also with hybrid or electric drive.

Keywords: alternative energy, micro sensors, thermoelectric generator.

Introduction

The transport sector is an extremely important part of the national economy for many reasons. Transport plays a crucial role bringing goods and services to customers as well as transporting passengers to work or acting for pleasure purposes [1]. Nowadays we record a large increase of individual automobile transport on roads [2], especially in development countries and for this reason the movement of vehicles in cities is slow during the rush hours [3]. Apart from the unquestionable advantages, transport also has significant disadvantages. The most important of them are road accidents, the phenomenon of transport congestion, noise emissions and negative impact on the natural environment. Environmental pollution, depletion of natural resources and the increase in the amount of waste upset the balance of the natural environment [4]. Moreover, the transport sector plays an important role in the development of any country, but at the same time consumes a significant amount of energy and is the main source of environmental pollution [5]. Europe, as the world pioneer in this fight, is working hard to reduce greenhouse gas emissions, setting a good example for other countries and regions [6]. Constant technical development forces an increase in energy demand, which in turn prompts us to look for new solutions in the field of using and recovering energy from various technical systems. These searches occur in many sectors of the economy and concern various technical objects. Transport, which is one of the most important elements of development, also contributes to environmental issues and energy waste [7]. Currently, the automotive industry is undergoing a huge transformation, it manifests itself in the development of new drive systems (hybrid and electric) and in the improvement of piston internal combustion engines, both with spark ignition [8-10] and self-ignition [11; 12]. Another large area of interest is the search for alternative fuels to crude oil. The use of alternative fuels is one of the main solutions currently allowing the reduction of pollutant emissions [13]. In many scientific papers the subject of the research is using various alternative fuels [14; 15; 16; 17], and reduction in the consumption of lubricating oils and plastic lubricants [18]. For many reasons, there is a growing interest in plant-derived fuels (biodiesel) [4; 19-22], gaseous fuels, e.g., LPG (Liquefied Petroleum Gas) [13; 17] or CNG (Compressed Natural Gas) [5; 21].

The development of piston internal combustion engines manifested itself particularly in the improvement of fuel supply systems [10; 12], exhaust gas treatment systems and diagnostic systems (OBD and OBDII) [23]. In the automotive sector, numerous methods can be applied to the measured signal in the time domain [24]. Recently, the analysis of vibration signals has been widely used for diagnostic purposes of various engine units and systems, as well as other vehicle systems, e.g., gearbox or suspension. Many researchers use methods such as the Fourier transform and the wavelet transform [25-27], and Hilbert transform [28-30] or neural networks [31] for fault detection and operational parameters in rotating systems. Noteworthy are the papers in which the authors diagnosed fuel supply systems using vibration signals [21; 32] and charge exchange in the combustion chamber [33; 34]. Balytskyi and Abramek [32] investigated the degradation of the sealing ring as a result of the loss of working gases of the internal combustion engine. In the works [25; 35; 36], a vibration signal was used to analyse the technical condition of the gears of the transmission, also to diagnose the vehicle suspension systems [37; 38].

Reducing energy losses in motor vehicles is necessary to increase fuel economy, reduce emissions and ensure the power demand of other vehicle systems [16; 39-41]. In addition to improving the efficiency of the engine and drive system, we can also collect energy wasted in vehicles, such as recovering lost thermal energy [42-45], regenerative braking energy [46; 47] or vibration energy coming from the vehicle suspension shock absorbers [37; 38; 48-50]. The most popular energy recovery systems are based on the following types of converters:

- piezoelectric,
- ferromagnetic materials,
- electromagnetic,
- thermoelectric, etc.

Research directions – review of solutions and discussion

The main direction of the research in the automotive industry is obtaining energy from various vehicle components and the internal combustion engine. The previously lost energy can be used to power some on-board equipment or electrical sensors that monitor various functions in the vehicle. The main directions of recovery of energy lost in motor vehicles are:

- recovery of wasted heat energy,
- energy recovery during braking,
- energy from the vehicle suspension,
- vibration of the internal combustion engine, etc.

Modern internal combustion engines have an efficiency of about 40%, so most of the energy is dissipated, mainly in the exhaust and cooling systems. In terms of thermal losses in the exhaust system, numerous studies are underway to recover some of this energy and replenish electricity resources. Therefore, significant energy saving can be achieved by proper recovery of internal combustion engines (ICE) waste heat [51]. Among different waste heat recovery technologies, thermoelectric generator (TEG) has received much attention, because it is highly reliable and compact without any moving part and can directly convert heat into electricity [42]. Fig. 1 shows a schematic of the exhaust-based thermoelectric generator ETEG system (TEG modules, and heat source and heat sink channels are all included). 20 TEG modules are installed on both sides of the ICE exhaust channel (10 on each side) [42]. The exhaust channel serves as the heat source, and the air flows through the cooling channels (on top and bottom of the exhaust channel) acting as the heat sink. A presented TEG module consists of 160 TEG units, connected in series electrically and in parallel thermally. In this case A single TEG unit includes a p-type and n-type semiconductor, which are connected by a conductor (e.g., copper), and substrates (e.g., ceramic) are placed on the top and bottom for electrical insulation.

Vale et al. [44] investigated the energy transfer from the engine exhaust of two vehicles: a commercial 3.5 tonne and a heavy-duty 40 tonne vehicle, both simulated in ADVISOR [52] in constant speed and world harmonized transient cycle (WHTC) [53]. The effect of two different heat exchanger designs, with flat fins or offset stripes, on electrical power and net power output is assessed. The influence of the height, spacing and length of the ribs was investigated, as well as the influence of the width and length of the heat exchanger and the height of the thermocouple legs [44]. The analysis was carried out for steady-state conditions, assuming typical extra-urban driving speeds, mass flow rates, and exhaust gas and cooling water temperatures for both vehicles. In both tested cases, smooth and offset, a compromise is needed to achieve high electric power and net power at the same time. In the tested cases and with the criteria used, smooth fins provide better performance than offset strip tapes, especially as a result of pumping power. TEG size analysis shows that doubling the length to obtain maximum electrical power is more effective than doubling the width [44]. On the other hand, doubling the width is more effective when considering net power [44]. The analysis shows that for typical extra-urban driving conditions, as well as for the heat exchanger and external dimensions of the TEG found in the parametric study, the recovery efficiency is low [44]. The best reported recovery efficiency is about 2%, with an average thermoelectric material efficiency of about 4.4% for a light vehicle [44]. On the other hand, for a truck, the results obtained by means of parametric analysis show over 800 W of electrical power. This can be used to generate a demand for the vehicle's electrical network. Karri et al. [54] analysed the potential benefits of using TEG modules in an SUV (Sports Utility Vehicle) in steady state and generated 100-450 W of electricity, saving up to around 2.3% of fuel. Of course, the best results were obtained in trucks because they generate more exhaust gases, but passenger cars, especially used in city traffic, are also interesting.

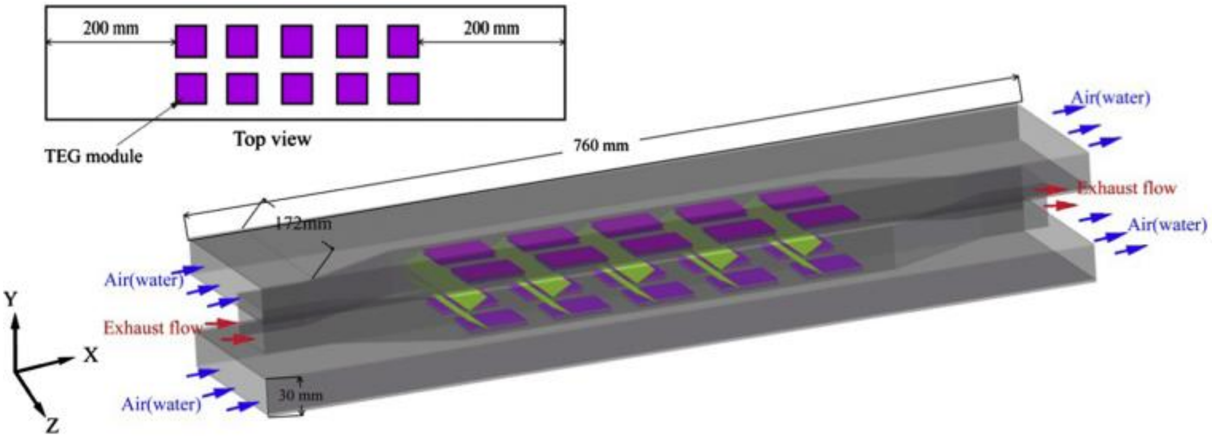

Fig. 1. **Schematic of exhaust-based thermoelectric generator system [42]**

Lu et al. [55] investigated two types of heat transfer enhancement structures, namely rectangular offset strip fins and metal foams, for the exhaust gas heat exchanger of a gasoline light-duty vehicle. It turned out that the electric power of the metal foams was much higher (approx. 130-294 W) than that of the offset tape terminals. The metal foams, however, produced a greater pressure drop, and while the total power output can increase significantly, the net power output is lower.

Bai et al. [56] used the Computational Fluid Dynamics (CFD) code to investigate the heat transfer and pressure drop for six different internal heat exchanger structures in a 1.2 dm^3 light petrol engine vehicle. They showed that the serial structure of the plate provides the highest heat transfer, but also the greatest pressure drop. They concluded that there is a trade-off between high heat transfer and low pressure drop. Su et al. [57] compared three internal heat exchanger structures for automotive exhaust-based TEGs: fishbone-shaped, accordion-shaped and scatter-shaped. The accordion-shaped design has been proven to provide a better even temperature distribution. In both of these studies, specific values of electric and net powers were not presented. Liu et al. [58] focused on the temperature distribution in the heat exchanger mounted on the exhaust of a 2.0 dm^3 naturally aspirated gasoline engine. The authors compared two internal heat exchanger geometries, fishbone-shaped and chaos-shaped, and concluded that the chaos-shaped structure leads to better results (value of the maximum electrical power is approx. 180 W).

Ibrahim et al. [59] studied the automotive exhaust heat recovery characteristics of thermoelectric modules using a rectangular exhaust gas channel. They found that the packing of a porous material inside the exhaust gas channel improves the thermoelectric energy conversion performance by boosting the heat transfer from the gas stream flowing in the hot-side duct to the surfaces of TEMs. Kim et al., [43] used a turbocharged six-cylinder diesel engine was used as the heat source; the engine was operated under various conditions and three engine rotation speeds – 1000, 1500, and 2000 rpm – were employed to determine the effect of the exhaust gas flow rate on the TEG power output. Based on the experimental results, a contour map was obtained showing the TEG output power as a function of engine load and speed. As a result, it was found that the power output of the TEG increases with the load or speed of the engine. The maximum power output was 119 W at 2000 rpm with a BMEP of 0.6 MPa; the maximum energy conversion efficiency in the range 0.9-2.8% [43].

In work [60] The waste heat recovery performance of a TEG equipped with a plate-type porous medium (perforated plate) was experimentally investigated. Experimental results show that at the highest engine rotation speed of 1400 rpm, a maximum power output of 98.3 W was obtained using the lowest porosity (0.121), and a maximum energy conversion efficiency of 2.83% was obtained using the optimal porosity (0.416) [60]. The conversion efficiency and power output of the TEG present can be maximized by using porous media with a porosity of 0.461 and 0.32, respectively. It has been shown that the use of a porous medium with a porosity < 0.32 in the current TEG configuration should be avoided because the back pressure would exceed the acceptable limit of 3 kPa for a passenger car. Fig. 2 shows an example of the TEG system with upstream diesel catalytic converter (DOC).

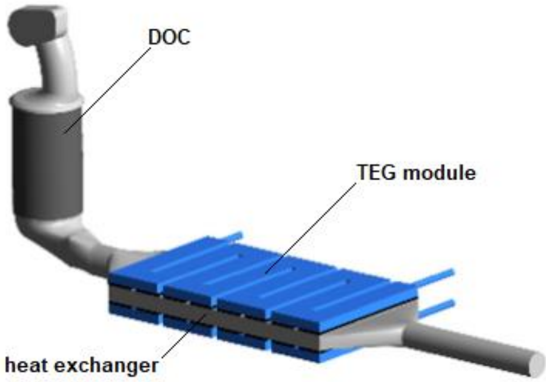

Fig. 2. **TEG system with upstream diesel catalytic converter, based on [61]**

The literature presents research related to the modelling of thermal waste energy recovery systems. Meng et al. [62] developed a multi-physics thermoelectric generator model in a control volume for automobile exhaust waste heat recovery. In this study a constant exhaust condition is considered and Bi_2Te_3 thermoelectric material is used. In particular, the number and size of thermocouples as well as the direction of flow in the heat exchanger on the cold side were analysed and discussed. The non-uniformity of temperatures along the flow direction and its influence on TEG performance are presented. Kumar et al. [63; 64] developed a numerical model for a TEG, also for steady state conditions from light-duty vehicle. Another steady state mathematical model of a TEG using the exhaust gas of vehicles as heat source was presented by Wang et al. [51]. Yu et al. [65; 66] developed a numerical model and found that the performance of TEG modules is improved with the increment of the vehicle (a pickup truck) speed: range 18-220 W when the speed increases from 20 $km \cdot h^{-1}$ to 120 $km \cdot h^{-1}$, and the transient behaviours of the TEG modules in different driving conditions were also investigated.

Ma et al. [67] investigated the effect of longitudinal vortex generators (LVGs) on the performance of a thermoelectric power generator (TEG) with a plate-fin heat exchanger. Overall, this work demonstrates that LVGs have great potential to enhance the performance of TEGs for waste heat recovery from vehicle exhaust. Under baseline operating conditions, the heat input and open circuit voltage of the TEG with LVGs are increased by 41-75% compared to a TEG with smooth channel [67].

Also, automotive concerns are working on energy recovery solutions in their vehicles. For example, BMW [68] has strategies to commercialize TEG-installed vehicles and merge the functions of the TEG and catalytic converters for improved system compactness. They have also been investigating the fabrication of high performance and eco-friendly thermoelectric modules (TEMs). General Motors [69] has developed a TEG with a rectangular configuration, targeting the Chevrolet Suburban, which features two different types of TEMs.

Conclusions

1. As the presented studies show, the height of the thermocouple arms plays a significant role in the thermoelectric behavior of the thermocouples, and the optimal height depends on the configuration that maximizes the electrical power. Similarly, the shape of the TEG elements of the solutions presented above showed the ranges of power obtained in the tested gasoline engines of motor

vehicles. Despite the fact that the obtained energy recovery values are not impressive (0.9-2.8%), they constitute an important element of the electricity demand in the vehicle.
2. Waste heat recovery equipment and cogeneration are effective techniques for energy recovery which to some extent improve the overall thermal efficiency of the system. However, there is still great potential for the storage and use of the thermal energy of the output stream by efficiently implementing appropriate waste heat recovery systems and improving the overall thermal efficiency.
3. Almost 60% of the input energy is wasted by the exhaust gases and coolant of internal combustion engines. As shown in the review, the energy yield from thermoelectric elements can average around 200 W for passenger cars, and in the range of 100-450 W electric energy for SUVs. The best results of waste energy yield are achieved by high-capacity diesel engines (energy yield approx. 800 W), which, apart from transport, are one of the most frequently used generation units.

Acknowledgements

This publication was supported by the program of the Polish Ministry of Science and Higher Education under the project DIALOG DIALOG 0019/DLG/2019/10 in the years 2019-2021.

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