State-of-the-Art and Future Trends of Thermoelectric Generation Systems in Automotive Industry

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Abstract. Recovery of the energy contained within the waste heat from various processes represents an important concern for the efficiency of energy utilization. This paper aims to present an overview of currently employed methods for waste heat energy recovery in the automotive industry, with an emphasis on processes within thermal combustion engines and recovery methods based on thermoelectric generators (TEG). While TEG technology is capable of direct conversion of heat into electricity, conversion efficiency is quite low. Efforts are made to optimize these systems (number, size, form, positioning, location, etc.) in order to minimize heat loss and maximize energy recovery. The review concluded that the efficiency of TEG conversion might be improved by choosing appropriate characteristics for the recovery system for specific processes analyzed, such as thermoelectric materials, geometry, location, and type of cooling fluid.

Keywords: Thermoelectric generator · Thermal management · Waste energy · Automotive

1 Introduction

Originally identified by Peltier in 1834, this phenomenon generates electrical power for thermoelectric devices (thermoelectric modules). In the past, semiconductor materials were rarely used to generate cooling or heating effects. Through the development of semiconductor materials, a wide range of thermoelectric refrigeration applications have become possible [1].

A semiconductor material's Seebeck coefficient and its absolute temperature determine the Peltier coefficient, which governs the Peltier effect. In the case of current flowing from an n-type material to a p-type material, there is a cooling effect, and in the case of current flowing from a p-type material to an n-type material, there is a heating effect. As the current direction changes, the temperature at the hot and cold ends of the circuit is reversed [2].

In a perfect world, the ratio of the Peltier coefficient [3] to the current running through the semiconductor material will determine how much heat is absorbed at the cold end

A. V. Sandu et al. (Eds.): ICIR EUROINVENT 2023, SPM 38, pp. 1–8, 2023.
https://doi.org/10.1007/978-3-031-45964-1_1

and how much heat is dissipated at the hot end. Two sources, conducted heat and joule heat, effectively limit the net quantity of heat absorbed at the cold end due to the Peltier effect. Heat will conduct through the semiconductor material from the hot to the cold ends as a result of the temperature difference between the cold and hot ends [4].

The Seebeck effect, which was first identified in 1821, is a property of thermoelectric devices that allows them to transform thermal energy from temperature gradients into electric energy. When there is a temperature difference between the hot and cold ends of a semiconductor material, a voltage is produced known as the Seebeck voltage. Thus, the Seebeck effect [5] really has the opposite impact as the Peltier effect. A thermoelectric device may also serve as a power generator as a result of the Seebeck effect. As a result of heating one junction, an electric current flow through the circuit, providing power to the device. As a matter of fact, a "module" is created by connecting a number of these thermocouples in series with each other [6].

A thermoelectric device (module) is typically built using more than one pair of semiconductors. Each semiconductor used in the module is referred to as a thermoelement, and a thermocouple is a pair of thermoelements [7].

2 State-of-the-Art

The thermoelectric generator (TEG), which is used for thermal energy harvesting, can directly convert heat into electricity. The thermopile, which is composed of thermocouples coupled electrically in series and thermally in parallel, is the basic structural component of TEG. Micro TEG (-TEG), which has the advantages of small volume and high output voltage, has attracted attention in the past 20 years as a result of the enormous advancements made in microelectromechanical systems technology.

One of the innovative technologies being used to cut gas emissions and manage the effects of global warming is the thermoelectric generator (TEG) [8]. TEGs use a direct, ecologically friendly conversion of thermal energy into electrical energy to implement the Seebeck effect [9]. TEGs have various benefits in addition to not having an influence on the environment. They are adaptable in terms of size and design and have a long lifespan due to the lack of moving components, circulation fluids, or chemical compounds. TEGs are built of numerous thermopiles, and each thermopile has a number of thermocouples that are coupled electrically and thermally in series and parallel, respectively, as shown in Fig. 1, [10–12].

A semiconductor material's capacity for refrigeration depends on the interaction of its Seebeck voltage, electrical resistivity, and thermal conductivity throughout its operational temperature range between the cold and hot ends. The figure of merit Z is defined as the Seebeck coefficient squared divided by the electrical resistivity and thermal conductivity products. The figure of merit for each n- and p-type semiconductor material is temperature-dependent since each of their attributes changes with temperature. It can be demonstrated that the "temperature averaged" figure of merit of each semiconductor material is directly related to the largest temperature differential that a single pair of n-type and p-type materials may attain [13, 14].

As a result, the main goal in choosing and perfecting thermoelectric materials is to maximize the figure of merit. The heat pumping capacity of each n- and p-type

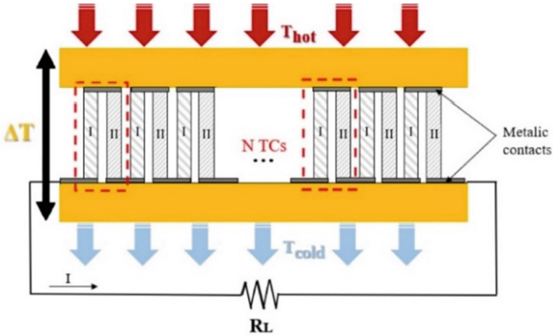

Fig. 1. Thermoelectric Generator (TEG).

semiconductor material is determined by its length-to-area ratio, while the temperature difference is constrained by the semiconductor material's figure of merit. A pseudo-binary alloy known as $(Bi,Sb)_2(Te,Se)_3$ is the most often used thermoelectric material for refrigeration in the temperature range of 120 to 230 °C.

P-type and N-type Bismuth Telluride thermoelements are connected electrically in series and thermally in parallel between the ceramic substrates in a conventional thermoelectric device, which is made up of two ceramic substrates that act as a foundation and electrical insulation. The dimensions range from 3 mm square by 4 mm thick to 60 mm square by 5 mm thick, and the maximal heat-pumping rate ranges from 1 to 125 W for conventional thermoelectric devices. The hot and cold sides can differ in temperature by a maximum of 70 °C. The devices range in thermocouple count from 3 to 127. It is possible to find multistage (cascade) series thermoelectric devices that can handle considerable temperature differences (up to 130 °C). About 100 °C is the lowest practicable temperature that may be reached.

Additionally, according to several studies, the majority of commercially available TEG modules manufactured of bismuth telluride have low operating temperatures (up to 260°C), a maximum figure of merit of 1.2, and low conversion efficiencies (up to 5%). Research on substitutes with superior temperature ranges and figures of merit, such as SiGe alloys, clathrates, skutterudites, and complementary metal-oxide semiconductors, is advised.

The vast majority of TEGs are used in various fields, such as Space Energy - where solar panels [15] are not sufficient, the thermoelectric generator is used to produce electricity in extreme conditions [16], such as in space travel [17–19].

Oil and gas industry - the thermoelectric generator is used to power sensors and other devices in extraction facilities, which are often in extreme conditions [20, 21].

Military technology - the thermoelectric generator [22] is used to power surveillance and communications devices in the field, where conventional power sources are not available. Medical industry - the thermoelectric generator is used in medical devices that need to operate in extreme conditions, such as sterilization rooms or blood cooling and heating devices [23–26].

Last but not least, these can be and are used in the Automotive Industry. The thermoelectric generator is used in hybrid and electric vehicles to charge the batteries, replacing the traditional alternator, which is less efficient at low temperatures, but much research shows that they have also been tried in vehicles with internal combustion engines. As we all know, some components in internal combustion cars have various areas where waste heat is dissipated without being reused to its full potential. In this respect, based on TEGs, research has been carried out by positioning these devices in the exhaust or engine compartment area, where the level of heat release is very high and high temperatures can be reached.

One of the first tests using a TEG was carried out by Nissan in 1998 [27] when they developed an advanced type of thermoelectric module based on SiGe for application to a gasoline engine. This module consists of 8 pairs of these SiGe elements, which are electrically connected in series and have a maximum electrical power of 1.2 W, with a standing temperature difference of about 300 degrees Celsius. The modules are arranged between an exhaust pipe with a rectangular cross section and a water jacket around the exhaust pipe.

Another study shows that the thermal efficiency of brakes (BTE) can be improved by TEG, as they can recover significant heat losses from old internal combustion engine vehicles. Sok and Kusaka [28] conducted an experimental and modeling analysis of thermal recovery in a 2.2 L diesel engine to maximize its performance by demonstrating that a thermoelectric module (TEM) layout in TEG must be optimized, taking into account a trade-off between increased pump loss and TEG effective power, in order to fully utilize TEG in the engine. First, a high-fidelity 1D TEG model is created, and a fresh approach to model calibration is suggested by leveraging condensed user-defined functions for flow friction and heat transfer. The TEG heat exchanger's measured thermal performances are replicated for a variety of fin pitches, Reynolds numbers, and inlet gas conditions.

To increase its BTE and power, the TEG model is coupled with a precisely calibrated engine. Peak BTE at 2250 RPM, 60% load, and BTE = 48.7% and 52.1 kW braking power are the conditions that yield the highest efficiency. These results are obtained under the base scenario without TEG. The 3-layer TEG type (1.5 A4 paper size, 150 mm height, 36 kg weight) produces 1.1 kW of effective power in an ideal 9×10 TEM configuration. Finally, a next-generation, extremely efficient hybridized diesel engine is developed that achieves a 1.1% BTE improvement without sacrificing output.

This article examines the capabilities of thermoelectric materials, such as their ability to recover lost energy, cool electronic equipment, and use a heat source to regenerate electrical energy by using the thermoelectric effect.

Authors Zhang and Zhao [29] conducted extensive research on the thermoelectric quality factor, figure of merit, and thermoelectric material properties. All these factors are highly significant in determining the ability to transfer heat into electricity as well as the efficiency of thermoelectric materials.

At the same time, the authors examine various thermoelectric material classes, including semiconductors, graphite-based materials, intermetallics, and organic materials. Thermoelectric materials have enormous promise for enhancing energy efficiency and lowering CO_2 emissions.

The influence of metal foam thickness inside an automotive exhaust gas line with external thermoelectric generators (TEGs) is quantitatively examined in this paper by

Buonomo et al. [30]. Considered is a forced convective regime two-dimensional steady state heat transfer problem in a porous medium inside a conduit. The study enables a comparison of metal foam's impact on TEG performance for various foam thicknesses, porosities, pore densities, and mass flow rates of exhaust gas. The findings are displayed as temperature and pressure drop profiles. The major parameters are estimated and used to represent TEG efficiency and electric power. The major conclusions demonstrate that the channel's wall temperatures significantly increase when metal foams are used. As a result, increases in TEG efficiency are seen for a variety of metal foam thickness values.

According to the authors, Fernández-Yañez, P et al. [31], the main goal of this research is to examine the potential of TEGs in light-duty diesel engines, where there is less energy accessible in the exhaust systems and more difficulty in achieving energy recovery. Additionally, the engine was tested far from the full-load curve in the region of the engine map that is most frequently employed for passenger automobiles. This work also fills in the gaps in the development and deployment of thermoelectric generator prototypes by offering a fresh, practical understanding of the flow inside TEGs and the impact of catalysts. A TEG was created using a distinct methodology that focused on both minimizing engine impact (not always taken into account) and increasing electrical power production. Using computational fluid dynamics (CFD), the main design issues for the devices in this scenario are identified, and the implications of size and internal topology are researched. An innovative and detailed module-by-module methodology was used to thoroughly validate the CFD model that calculates electricity production. The engine map's common driving situations region of high load, high engine speed can recover some energy, according to the results [31].

Another piece of research demonstrates the importance of on-board power generation in light of the growing trend of electrification in road vehicles. The performance of a unique temperature-controlled thermoelectric generator (TCTG) concept in a light duty vehicle is evaluated in the current work, as well its effects on fuel efficiency and GHG emissions under actual driving situations. Corrugated pipes integrated in a matrix of cast aluminum make up the new exhaust heat exchanger (HE) idea, and variable conductance heat pipes (VCHPs) serve as spreaders of extra heat along the longitudinal direction. Due to its ability to prevent overheating by dispersing heat rather than squandering it through by-pass devices, this technology appears to have pretty excellent potential for highly variable thermal load applications. In addition, it does not require gravity aid and has a form factor similar to conventional generators, which are differences from the group's earlier designs. With as much as 572 W and 1538 W of average and maximum electric powers during a driving cycle, respectively, and a very promising reduction of 5.4% in fuel consumption and CO_2 emissions, it also seems to be capable of delivering a breakthrough electric output for TEG systems in such light vehicles [32].

In general, this branch of renewable energy is growing, and solutions are being sought to reduce pollution levels in the first place, but in this part of the vehicle sector, the aim is to make maximum use of waste or waste heat, mainly from vehicles equipped with internal combustion engines. It must be recognized that research in this area has been limited in number and that the cost of producing these devices is quite high. For this reason, the search is on for the best way to make a thermoelectric generator that is productive for a vehicle but at the same time costs as little as possible, but so far good results have been achieved in this direction.

3 Conclusions

This review presents the current status of thermoelectric generators, as well as the Peltier and Seebeck effects used in several fields of activity, with the main emphasis on the field of road vehicles. We note that in this industry, attempts are being made to optimize a device based on a TEG using the Seebeck effect by positioning it in a vehicle with an internal combustion engine in the most suitable places, where heat is wasted in nature and the temperature difference is quite high. In the future, it is hoped to develop such devices to produce auxiliary electrical energy for the vehicle, which can be used in various forms but at the lowest possible production cost.

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