



Heat transfer enhancement of a modularised thermoelectric power generator for passenger vehicles



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HIGHLIGHTS

- Shape-adapted thermoelectric module for highly compact heat recovery exchanger assembly.
- Heat pipe-assisted heat transfer enhancement method for better power output.
- Highest power output ratio to the total volume of heat recovery exchanger.
- Cascaded thermoelectric system can be scaled and extended for various power output.
- Self-clamping design of thermoelectric module can solve the thermomechanical imbalances.

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ABSTRACT

Transport represents over a quarter of Europe's greenhouse gas emissions and is the leading cause of air pollution in cities. It has not seen the same gradual decline in emissions as other sectors. Recently, the thermoelectric power generation (TEG) technology emerges as an alternative solution to the emission reduction challenge in this area. In this paper, we present an innovative pathway to an improved heat supply into the concentric shape-adapted TEG modules, integrating the heat pipe technologies. It relies on a phase changing approach which enhances the heat flux through the TEG surface. In order to improve the heat transfer for higher efficiency, in our work, the heat pipes are configured in the radial direction of the exhaust streams. The analysis shows that the power output is adequate for the limited space under the chassis of the passenger car. Much effort can also be applied to obtain enhanced convective heat transfer by adjusting the heat pipes at the dual sides of the concentric TEG modules. Heat enhancement at the hot side of the TEG has an effective impact on the total power output of the TEG modules. However, such improvements can be offset by the adjustment made from the coolant side. Predictably, the whole temperature profile of TEG system is subject to the durability and operational limitations of each component. Furthermore, the results highlight the importance of heat transfer versus the TEG power generation under two possible configurations in the passenger car. The highest power output per repeat unit is achieved at 29.8 W per 0.45 L with a ZT value 0.87 for a Bi₂Te₃-based thermoelectric material in our studies. The study provides an insight into a structurally achievable heat exchanger system for other high-temperature thermoelectric materials.

1. Introduction

Thermoelectric heat recovery, as one of the most promising clean technologies, has drawn great attentions due to its unique merits of energy conversion [1]. Unlike the traditional fossil fuel energy systems, TEG devices converts waste heat directly into electricity through the Seebeck effect of the semiconductor materials whereby a temperature

difference is maintained between the hot and cold side of the TEG module [2]. The TEG devices have the advantages of silent operation and they have no moving or mechanically complex components enabling them lasting for a very long time. They also operate at wider operational temperature range than most existing energy recovery systems [3,4]. There are several existing researches that have proved the feasibility of applying the TEG devices for waste heat recovery from

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vehicles. Agudelo et al. [5] and Stevens et al. [6] analysed the potential for energy recovery from the exhaust gases and the theoretical limit of thermoelectric generators for a given exhaust system configuration. The results show that the muffler has the greatest exergy loss making it the ideal place where waste energy can be recovered in the exhaust system. Additionally, there is an optimum number of thermoelectric leg pairs that maximize the power extracted for any TEG system.

However, each technology has its own advantages and challenges. The major challenge of the TEG device is its relatively low heat to electricity conversion efficiency. Recent years have witnessed impressive progress in thermoelectric materials. There have been many researches covering different aspects of thermoelectric materials, including bulk thermoelectric materials, individual nanostructures, and bulk nanostructures [7]. Nonetheless, there is still space for innovation and development of thermoelectric materials to take advantage of their solid-state nature, scalability and environmental friendliness in the automotive industry [8]. It could be highly anticipated from such material development that the TEG system would be applied in automotive waste heat industry in near future, if other challenges are addressed. Furthermore, in practice, the financial viability is highly sensitive to source temperature, device efficiency, maintenance cost, and the projected device lifetime. Benday et al. [9] presented a new methodology for the systematic study of thermoelectric generator economic analysis. This study provided a platform for analysing the performance of real-world systems and can be used to predict where further technological development on TEG materials and devices would be most effective. Huang et al. [10] presented a regenerative concept for TEG systems. It is found that the regenerative TEG systems can achieve power output which is similar with other TEG systems by using high temperature TE materials and guarantee a lower cost.

Despite the increasing research on thermoelectric materials, there are still many device-level challenges that prevent TEG devices from being applied in real applications. There are many researchers who focus on the numerical simulation of the performance of the TEG devices [11–13]. Hogblom et al. [14] established a simulation methodology for characterization and simulation of TEG systems allowing accurate prediction of the voltage and current as well as the heat flow at steady state. Zhang [15] first developed a numerical model which has taken into account the influence of temperature-dependent material properties, spatial-dependent heat flow rate in thermoelements and the heat and electricity losses at the junctions for performance calculation of the TEG devices. Liang et al. [16] presented a mathematical model of two-stage TEG and the performance of the two-stage TEG is analysed by simulating the effect of relevant factors as well. The results show that the output power and conversion efficiency of the two-stage TEG are higher, compared with the single-stage TEG. Yu et al. [17] investigated the transient behaviour of TEG system in different start-up modes by using the different heat transfer coefficient related to the engine speed. It is concluded that a higher vehicle speed improves the TEG performance in addition to accelerating the transient response. Liu et al. [18] developed an approach for integrating computer-aided analysis with an optimisation method that could be applied to the design and optimization of thermoelectric generators. This approach was applied to the multi-objective and multi-parameter optimization of geometric thermoelectric generators to design an optimal structure for TE modules. The results showed that the power outputs of the optimal design were about 5.7%, 5.0%, 9.4%, 18.9%, 28.9%, and 30.6% higher, respectively, than the initial design values. However, the improvement in power output reduced the conversion efficiency.

In addition to the numerical simulation research, there are also several researchers who have investigated the performance of TEG devices by experimental tests. Liu et al. [19,20] performed experimental study on different structural designs of heat exchanger in order to improve the efficiency of TEG system in which a maximum power output of 944 W is obtained in the revolving drum test under real working condition. Montecucco et al. [21–23] analysed the impact of

thermal imbalance on the power produced at module and system level of a TEG array in series and parallel. Experimental results clearly demonstrate that the temperature-mismatch situation creates a power production drop of 9.22% and 12.90% for the series and parallel cases respectively. Wang et al. [24] performed a serial experimental test on a new type of open-cell metal foam-filled plate heat exchanger based thermoelectric generator system. The results show that the heat exchange efficiency of 83.56% between heated air and cold water is achieved.

Other than the progress in the simulation and experimental study of the performance of TEG devices, the heat transfer performance has also been paid close attention. In most cases, it is poor heat transfer design that inhibits achieving the ideal efficiency. Accordingly, thermal scientists and system engineers focus mainly on enhancing the heat transfer to and from the TEG devices in order to improve the overall efficiency of the vehicle TEG systems [25]. Beyond the heat transfer enhancement, the novel design of the heat exchanger for TEG devices has been carried out as well. Aranguren et al. [26] built a new thermoelectric generator prototype which could produce 21.56 W of net energy covering 0.25 m² of space. In terms of heat dissipation, with the usage of the heat pipes in the finned heat exchanger, a 43% more net power is obtained. Ma et al. [27] investigated the effect of longitudinal vortex generators (LVGs) on the performance of a TEG with a plate-fin heat exchanger numerically. The results indicated that the heat input and open circuit voltage of the TEG with LVGs are increased by 41–75% compared to a TEG with smooth channel. Tian et al. [28] proposed a new waste heat recovery system with a heat pipe exchanger which is applied to recover thermal energy in high temperature industrial exhaust gas. After three-month of continuous operation, the heat pipe exchanger is observed to save 15% natural gas without any blockage of the gas side channel. In addition to the notable TEG performance discussed so far, the existing TEG systems are often too bulky to be applied in the exhaust system. Ali et al. [29] introduced a new innovative design of the thermoelectric generator incorporating the extended pin with segmented pin configuration. The new design allows the device operating at two different cold junction temperatures. Wang et al. [30] presented an innovative design of a cylindrical TEG heat exchanger which is applied to light duty passenger cars. An effective solution for enhancing the heat transfer of gas flow in the radial direction to the TEG is proposed in their research. Huang et al. [31] have investigated the electrical performance between different shapes of TE module, the results indicate that the open circuit electric potential of the annular TE module is 17% higher than that of the square TE module. Most of the existing researches are based on the numerical and experimental analysis of the influence of external conditions such as temperature and mass flow rate of heat exchanger for exhaust TEG system. However, the installation space and weight of the TEG system are rarely discussed. In practice, there is a very limited space in the vehicle exhaust system and therefore it should be optimized. Moreover, the weight of the TEG is also a vital factor in an effort to achieve the fuel economy [32].

To improve the defects of existing vehicular TEG systems, a light weight heat exchanger is significant for the development of vehicular TEG systems. Therefore, in the current work, a novel design of a concentric cylindrical TEG system is presented for use in the automotive exhaust system. Instead of using a bulky and heavy heat exchanger, the novel TEG system has a compact and lightweight heat sink which is assisted by heat pipes. As a reliable and efficient heat transfer component, heat pipes have been widely used for the thermal management of electronic devices. Heat pipes have the advantageous in that they have high heat conductivity, fast thermal response, and are light weight [33,34]. The combination of heat pipes with heat exchanger is projected to reduce the weight of the TEG system and the whole vehicle as well, consequently improving the fuel economy.

The proposed design is capable of adapting to the shape of the exhaust pipe besides accommodating more TEMs in the same installation length. In this paper, the numerical studies about the heat transfer

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