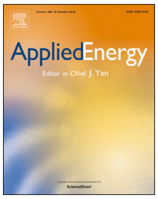
Applied Energy 229 (2018) 264–280

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Numerical analysis of the effects of electrical and thermal configurations of thermoelectric modules in large-scale thermoelectric generators

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HIGHLIGHTS

- Simulations of large scale automotive thermoelectric generators have been performed.
- The methodology of the numerical model has been validated experimentally.
- Thermal and electrical combinations of thermoelectric modules have been analyzed.
- There is an optimum number of thermoelectric modules beyond which power decreases.
- An approach for the mixed configuration that improves recovery energy is proposed.

ARTICLE INFO

Keywords:
TEM
TEG
Series parallel connection
Electrical thermal topology

ABSTRACT

The need to reduce both energy consumption and greenhouse gas emissions has boosted the interest in using thermoelectric generators (TEGs) as waste heat energy harvesters. High-power TEGs are usually formed by an array of commercial thermoelectric modules (TEMs). Recent studies have analyzed the effects of using different types of electrical connections between TEMs in TEGs to produce electric power, but the effects of using different thermal configurations between TEMs have not been fully examined. Here, both electrical and thermal effects have been investigated using a numerical model developed with GT-SUITE software, which has been validated with laboratory data. TEGs with a number of TEMs between 1 and 100 distributed in different patterns along the exhaust pipe have been simulated under three engine regimes. For a given TEM geometrical pattern and engine regime, results prove the existence of an optimum number of TEMs, beyond which the total extracted power decreases. A mixed spatial distribution of TEMs generates more power than either the pure series or the pure parallel topologies. Finally, a methodology is proposed to choose an appropriate pattern of TEMs for a TEG installed in a system with variable regimes. This method is applied to a mid-size automotive diesel engine.

1. Introduction

Internal combustion engines effectively convert one third of the fuel energy into mechanical work [1]. The remaining energy corresponds to heat losses, of which the exhaust system accounts for approximately one third of the primary energy [1]. The need to manufacture more efficient vehicles that meet environmental regulations has encouraged research focused on developing technologies to recover energy from exhaust gases [2]. Thermoelectric generation is among the most promising techniques [3].

A thermoelectric module (TEM) is a system formed by pairs of *n*- and *p*-type semiconductors that converts thermal energy into electrical energy by means of the Seebeck effect [4]. The assembly of one or more TEMs between a heat source (hot side) and a cooling system (cold side) in a single device and connected to an external electrical load is known as a thermoelectric generator (TEG) [5]. The size of this external electrical load determines the amount of power the TEG extracts. For given electrical and thermal connections of TEMs, the maximum power point (MPP) method consists in tuning the size of the external electrical load to maximize the TEG electrical output power.

Most of automotive TEGs currently tested are based on commercial TEMs. With the purpose of improving the heat transfer through TEMs, new TEG designs include the use of heat pipes [6] and the substitution of fins for dimples in the hot heat exchanger [7]. As heat is being extracted from the exhaust, the gas temperature decreases along the flow direction. This implies that TEMs of the same TEG work under

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https://doi.org/10.1016/j.apenergy.2018.07.116
Received 16 April 2018; Received in revised form 13 July 2018; Accepted 29 July 2018
0306-2619/

substantially different hot side temperatures depending on their location. The consequences of this mismatch in the TEM working regimes have been numerically investigated either by uncoupling the electrical system from the thermal one (i.e., fluid flow calculations independent of the TEM response [8]) or by coupling both the electrical and the thermal systems but with some simplifications (e.g., constant heat transfer coefficients [9]; single and continuous thermoelectric modules [10]; temperature-independent material properties [11], etc.). These previous works have provided valuable insights into the unequal functioning of TEMs in an automotive TEG. However, a fully coupled electro-thermal model, like the one used here, is required to comprehensively simulate a realistic automotive TEG.

There are multiple ways of electrically and thermally connecting TEMs in a TEG. The concepts of series, parallel and mixed electrical connections are well known. With regard to the thermal configuration, the connection in series implies an arrangement of TEMs aligned with the direction of the heat flow (i.e., along the exhaust pipe), the parallel connection implies a distribution of TEMs such that all of them are exposed to the same quantity of available heat (i.e., TEMs located in a plane perpendicular to the heat flow), and the mixed thermal array refers to any combination of TEMs distributed parallel and perpendicular to the direction of the heat flow. In TEGs formed by a large number of TEMs (n_{TEM_s}), the effects of the electrical and thermal connections of TEMs on the output electrical power are not totally known. Thus, it is a challenging task to find a general rule to determine the best electrical and thermal configuration of TEMs in a TEG.

Recently, Chen [12] numerically analyzed the output power of TEGs formed by 48 TEMs in 16×3 and 8×6 configurations (longitudinal × perpendicular to the flow) with two mixed electrical connections (series-first-parallel-second SFPS and parallel-first-series-second PFSS). In addition, Chen [9] assigned two possible values for the temperature difference across each TEM (ΔT_{TEM}): 23 °C or 223 °C. For the case of 10 TEMs with $\Delta T_{TEM} = 23$ °C, he obtained a 7% (13%) variation of the output power when changing the location of these TEMs in the SFPS (PFSS) connection case. He concluded that the TEG design with a SFPS connection type should uniformly distribute those TEMs with low ΔT_{TEM}, whereas in the FPSS case, the TEMs with low ΔT_{TEM} should be concentrated in columns.

Montecucco et al. [13] studied the impact on the power generated when three TEMs, each one with a different ΔT_{TEM}, were electrically connected either in series or in parallel. They observed power production drops of 9.2% (series) and 12.9% (parallel) from the maximum power obtained when each TEM was controlled individually, and concluded that the electrical connection in series is the most adequate. On the other hand, Stevens et al. [14] developed a thermoelectric analytical model to determine the theoretical limit of a TEG's electrical power generation, which is obtained when each TEM has its own tunable electric external load. The configurations analyzed in [14] involved several TEMs electrically connected either in series or in parallel and thermally connected in series. They found that there is an optimum n_{TEM_s} beyond which the total power extracted decreases. This maximum of the generated power becomes greater when the series electrical connection is adopted.

Other studies involving TEGs have combined different electrical connections, although with a fixed thermal topology. Deng et al. [15] experimentally and numerically analyzed the impact of module property disparity (i.e., TEMs with different Seebeck coefficients and internal resistance) and of wire resistance on the maximum output power. They concluded that the parallel connection suffered larger power losses in the wiring system. Quan et al. [16] and Fang et al. [17] developed algorithms to find the electrical connection of TEMs that optimized the output power of an automotive TEG (64 TEMs in [16] and 60 TEMs in [17]). Both studies concluded that the pure series electrical connection provided higher output power than the pure parallel one, with an optimal mixed electrical topology that increased the pure series figures by 9% [16] and 20% [17]. Recently, Negash et al. [18] experimentally studied the consequences of modifying the electrical connections of a TEG formed by 10 TEMs exposed at different ΔT_{TEM}. Maximum power was obtained with balanced TEM modules and a small number of junctions.

Previous works have mainly focused on studying the effects of electrical connections between TEMs. As far as we know, the only theoretical study that has investigated the implications of changing the spatial distribution of TEMs in a TEG was not suitable for a heat recovery system of exhaust gases, since it neglected the interaction of TEMs with both hot (exhaust gases) and cold (cooling system) flows [12]. Therefore, the main novelty of this work is the study of the consequences of using different TEM distribution patterns on the TEG output power with a fully coupled model. For this reason, we carry out analyses with series, parallel, square hybrid and mixed configurations for both the electrical connection and the thermal one. For the thermal connection, the term square hybrid describes a mixed configuration in which the same number of TEMs is distributed in parallel and in perpendicular with respect to the heat flow direction. In the square hybrid electrical connection, a group of TEMs located in the perpendicular plane with respect to the flow direction are electrically connected in parallel and, after that, electrically connected in series with the following group of TEMs.

Table 1 summarizes the main findings of these previous works. We have added an improvement ratio that considers the MPP value of the series electrical connection ($\mathrm{MPP_s}$) as a baseline value. For given thermal topologies, Refs. [16–18] found that mixed electrical connections, in some cases achieved by applying optimizing algorithms, improve the value of the $\mathrm{MPP_s}$.

The purpose of the present work is to determine the effects of electrical and thermal connections of TEMs on the output power of a given TEG that recovers waste energy from exhaust gases. The goal is to establish a criterion for recommending the electrical and thermal configurations of TEMs in a given TEG.

The paper is organized as follows. In Section 2, the TEG numerical

Table 1
Summary of previous works focused on the effects of the electrical and thermal connections of TEMs on the TEG output power.

Reference	n_{TEM_s}	Method[a]	Electrical connection	Thermal connection	Improvement ratio[b] (%)
[12]	48	Num	Mixed	Mixed variable	–
[13]	3	Exp	Series and parallel	Series fixed	0
[14]	1–80	Num	Series and parallel	Series fixed	0
[15]	2	Exp	Series and parallel	Parallel fixed	0
[16]	64	Exp	Series, square hybrid and mixed	Square hybrid fixed	9
[17]	60	Exp/num	Series, parallel and mixed	Mixed fixed	20
[18]	10	Exp	Series, parallel and mixed	Mixed fixed	1
Present work	1–100	Num	Series, parallel, square hybrid and mixed	Series, parallel, square hybrid and mixed	0–68

[a] Num = numerical simulations; Exp = experiments.

[b] $(\mathrm{MPP_{max}} - \mathrm{MPP_s})/\mathrm{MPP_s} \times 100$ where $\mathrm{MPP_{max}}$ is the maximum value of MPP found for all the studied configurations and $\mathrm{MPP_s}$ is the MPP corresponding to the series electrical connection.