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Constant heat characterisation and geometrical optimisation of thermoelectric generators

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HIGHLIGHTS

- In most waste heat applications at any time the maximum available heat is limited.
- The performance characterisation of TEGs with constant thermal power is presented.
- The influence of the geometrical parameters is analysed.
- The pellets number and geometry are optimised for limited heat systems.
- The efficiency and output power are maximized and the material needed is minimised.

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ABSTRACT

It is well known that for a thermoelectric generator (TEG) in thermal steady-state with constant temperature difference across it the maximum power point is found at half of the open-circuit voltage (or half of the short-circuit current). However, the effective thermal resistance of the TEG changes depending on the current drawn by the load in accordance with the parasitic Peltier effect.

This article analyses the different case in which the input thermal power is constant and the temperature difference across the TEG varies depending on its effective thermal resistance. This situation occurs in most waste heat recovery applications because the available thermal power is at any time limited.

The first part of this article presents the electrical characterisation of TEGs for constant-heat and it investigates the relationship between maximum power point and open-circuit voltage. The second part studies the maximum power that can be produced by TEGs with pellets (or legs) of different size and number, *i.e.* with different packing factors, and of different height. This work provides advice on the optimisation of the pellets geometrical parameters in order to increase the power generated, and consequently the thermodynamic efficiency, and to minimise the quantity of thermoelectric material used, for systems with limited input thermal power.

1. Introduction

Thermoelectric generators (TEGs) are recently being utilised to recover waste heat in a multitude of applications, ranging from low power (sensors [1,2] and battery charging [3]) to medium power (automotive [4,5], stoves [6,7], CHP systems [8], and combined to TPV [9] or PV [10] systems) to high power (heavy-industry [11] and geothermal [12]) because of their reliability, small size and weight, and modular scalability [13].

For a given temperature difference the electrical power delivered by the TEG varies depending on the current drawn by the electrical load connected to its terminals. The TEG can be electrically modelled in thermal steady-state as a voltage source in series with an internal resistance [14,15]. In available literature, to maximise the electrical power extracted from the TEG at any fixed temperature difference the load's impedance should equal the TEG's internal resistance, as stated by the *'maximum power transfer'* theorem [16]. Hence the maximum power point lies at half of the open-circuit voltage V_{OC} or equivalently at half of the short-circuit current I_{SC}.

A characterisation showing the relationship between electrical power, voltage and current for a constant applied temperature difference is an established method to specify the performance of TEG devices. When physically obtaining this characterisation it is necessary to adjust the thermal power through the device because

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Nomenclature

ΔT	temperature difference (K)
κ	thermal conduction coefficient (W/mK)
l	length (or height) of pellets (or legs) (mm)
L	thickness of the TEG (mm)
K	thermal conductance (W/K)
R	electrical resistance (Ω)
α	seebeck coefficient (μV/K)
a, b, c	parameters for the calculation of V_{OC} (V/K^2, V/K and V, respectively)
d, e, f	parameters for the calculation of R_{int} (Ω/K^2, Ω/K and Ω, respectively)
N	number of pellets in a thermoelctric device
τ	clearance space between pellets (mm)
ω	side length of a pellet (mm)
A	cross-sectional area (mm^2)
V	volume (mm^3)
ϕ	pellets packing (or fill) factor
ZT	dimensionless thermoelectric figure of merit

a change in electrical load varies the effective thermal conductance of the TEG due to the Peltier effect [17]. This method of characterisation is referred to as constant temperature operation, and its use effectively masks the complex and subtle device response to variable load current. The internal resistance (R_{int}) is the inverse slope of the V-I line obtained from this electrical characterisation, and its absolute value is dependent on the average temperature at which the TEG is operating. When the TEG is operated to the left of the maximum power point as shown in Fig. 1, reduced current flows through the TEG and the effective thermal conductivity of the TEG (which depends also on the current flow, due to the parasitic Peltier effect) decreases. Under this condition the thermal energy conducted via the TEG is less than that at the maximum power point and hence a lower thermal load is imposed on the overall system. This is advantageous in most circumstances since it leads to increased thermal efficiency of the system. When the TEG is operated to the right of the maximum power point the thermal conductivity increases and the thermal energy conducted via the TEG is greater than that which flows at the maximum power point. Operation in the region to the right on Fig. 1 leads to a reduced thermal efficiency of the system. For the module data (product code: GM250-449-10-12 by *European Thermodynamics Ltd.*) shown in Fig. 1, the maximum power is approximately 13.2 W with a corresponding output voltage of 16.5 V (being half of the open-circuit voltage of 33 V).

In most practical applications, however, and especially in automotive exhaust gas energy recovery systems, TEGs are subject to limited thermal input energy rather than to a constant temperature difference. This is referred to as ‘‘constant heat’’ operation. Kumar et al. [18] observed strong variations of the electrical power generation with the exhaust gas flow rate and temperature, *i.e.* the input thermal power. The available thermal energy may change with time, but its rate of variation will be orders of magnitude slower than the TEGs electrical response [19]. In considering the constant heat condition, changing from open-circuit to at-load operation results in a smaller temperature difference across the device, due to its greater effective thermal conductivity. The change of temperature difference after a transient that could last for several seconds thus leads the device to produce lower electrical power.

Mayer and Ram [20] firstly noticed that when the temperature gradient across the TEG is not constant the optimum current is lower than that required for constant temperature systems. Moreover, they found that this optimum load also differs from the load that maximises efficiency in constant temperature systems. They also provided guidance on the optimisation of the pellet length per unit area. Similar results about optimum load condition are reported by Gomez et al. [21]. They compared a model in which the temperatures are constant with a model in which the temperatures on the sides of the device vary depending on the load, while the ambient temperature and the hot-source temperature (separated from the TEG by thermal resistances) are constant. We proposed similar results about the influence of the load on the temperature profile -with a different analytical solution that can also simulate time transients- in [22].

Yazawa and Shakouri [23] optimised the thermoelectric device design together with its heat source and heat sink at constant temperatures. They concluded that the optimum operating load is when $R_{load} = R_{int}\sqrt{1+ZT}$, where R_{int} is the internal resistance and ZT is the figure of merit of the thermoelectric device. They also suggested that using low fill (or *packing*) factors could increase the electrical power output per unit mass. McCarty [24] confirmed Yazawa's result and provided equations to calculate the optimum number of couples and pellets length-to-area ratio as functions of the total thermal resistance of the system and for fixed electrical load, hot-side temperature and material properties. However, the value of $ZT = \sigma\alpha^2 T_{AVG}/\kappa$ depends on the electrical conductivity (σ), the Seebeck coefficient (α), the thermal conductivity (κ) and the average temperature of the semiconductor material, T_{AVG} (in degrees Kelvin), therefore it is difficult to calculate its correct value before knowing the effective operating temperatures. Nemir and Beck [25] explained that the maximum efficiency in constant temperature is dependent only on the temperatures and ZT, but not on the particular values of σ, κ and α. They also investigate the influence of thermal interfaces but they do not analyse the variations on thermal power through the TEG. Apertet et al. [26] complemented this analysis.

The previous literature reported here ([20,21,23–26]) effectively considered a system in which the thermal input power varies depending on the load, because the hot-source temperature and cold-source (often ambient) temperature are maintained constant (ideal temperature sources). For such reason maximum power and maximum efficiency are at different points. On the contrary, in constant heat systems the point that maximises the electrical power output also guarantees maximum efficiency, as introduced by Wang et al. [27] and further described in this article.

Despite high ZT values recently claimed by thermoelectric material scientists, there is not much literature focused on improving the thermoelectric device design and architecture. Rezania et al. [28] focused on the single thermoelectric element to optimise the ratio of the cross-sectional areas of the *p*- and *n*-semiconductor pellets; they concluded that maximum power generation occurs when the area of the *n*-pellet is smaller than that of the *p*-pellet, due to lower electrical resistance and higher thermal conductivity of the *n*-type material considered. Lee [29] focused on the design of thermoelectric devices in conjunction with the heat sinks performance, asserting that there is an optimal ratio of system thermal conductivities to provide maximum power output. Jang and Tsai [30] and Favarel et al. [31] modify the spacing between TEG modules (or the occupancy rate) placed on a heat exchanger of fixed geometry to maximise the power output depending on the available thermal power. Kajihara [32] presented an analysis of the influence of legs' width, height, gap (clearance) and number