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The effect of temperature mismatch on thermoelectric generators electrically connected in series and parallel

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HIGHLIGHTS

- We study the electrical connection of thermoelectric generators (TEGs) in series and parallel arrays.
- We analyse the electrical characteristic of TEG arrays under mismatched temperature gradients.
- We experimentally quantify the power loss due to temperature mismatch in TEG arrays.
- We provide equations to estimate the electro-thermal effects that occur in each TEG within the series or parallel array.
- We discuss advantages and drawbacks of TEG arrays in series and parallel.

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ABSTRACT

The use of thermoelectric generators (TEGs) to recover useful energy from waste heat has increased rapidly in recent years with applications ranging from microwatts to kilowatts. Several thermoelectric modules can be connected in series and/or parallel (forming an array) to provide the required voltage and/or current. In most TEG systems the individual thermoelectric modules are subject to temperature mismatch due to operating conditions. Variability of the electro-thermal performance and mechanical clamping pressure of individual TEG modules are also sufficient to cause a significant mismatch. Consequently, when in operation each TEG in the array will have a different electrical operating point at which maximum energy can be extracted and problems of decreased power output arise.

This work analyses the impact of thermal imbalance on the power produced at module and system level in a TEG array. Experimental results clearly illustrate the issue and a theoretical model is presented to quantify the impact. The authors believe the experimental results presented in this paper are the first to validate a rigorous examination of the impact of mismatched operating temperatures on the power output of an array of thermoelectric generators.

1. Introduction

Thermoelectric generators (TEGs) produce a current flow in an external circuit by the imposition of a temperature difference ΔT across the TEG. The magnitude of this ΔT determines the magnitude of the voltage difference ΔV and the direction of heat flow determines the voltage polarity.

The use of TEGs to recover waste heat energy has increased rapidly in recent years with applications in fields such as remote sensing [1–3], automotive [4–7], stove [8,9], geothermal [10], space systems [11] and industrial power plants [12–14]. Thermoelectrics are lately also combined to PV, solar thermal or thermophotovoltaic systems [15–17]. The power requirements depend strongly on the application, but span the range from microwatts to kilowatts. In systems where more than a few Watts are needed, several thermoelectric modules are deployed in arrays with series and/or parallel interconnections in order to provide the required power level. The method of interconnection of the TEGs is usually determined by the voltage and/or current required. The TEG can be electrically modelled as a voltage source in series with an internal resistance [18,19], as shown in Fig. 1. The values of both the voltage produced and the internal resistance vary with temperature.

The Peltier effect acts to pump heat from one side of the TEG to the other according to the current flowing through the device. As a consequence, the effective thermal resistance of the TEG depends to a certain extent on the magnitude of the current flowing in the external circuit [20,21]. In a thermoelectric generator the Peltier effect is considered to be parasitic and unwanted. Low electrical current will lead to a reduced thermal conductance

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Nomenclature

ΔT	temperature difference (K)
V_{OC}	open-circuit voltage (V)
I_{SC}	short-circuit current (A)
R_{int}	internal resistance (Ω)
α	seebeck coefficient (μV/K)
a, b, c, d, e, f	constant coefficients independently calculated for each TEG
I_{load}	load current (A)
V_{load}	load voltage (V)

(high thermal resistance; low heat pumping), and high electrical current will lead to an increased thermal conductance (low thermal resistance; high heat pumping). If the TEG is electrically short circuited, the TEG will have the highest possible thermal conductance. This condition is normally avoided because it leads to a very inefficient thermal circuit with a large amount of heat energy being transferred from the 'hot' to the 'cold' side with no benefit in electrical power generation.

For a given thermal operating point the electrical power delivered by the TEG varies according to the current drawn by the electrical load. To maximise the power produced by the TEG, the electrical load impedance should equal the TEG's internal resistance (this is known as the "Maximum Power Transfer Theorem") [22,23]. The Maximum Power Point (MPP), the point at which the TEG delivers the maximum possible power to the external load for a given temperature) is given by half the open circuit voltage, $V_{OC}/2$, or by half of the short circuit current, $I_{SC}/2$.

Maximum power point tracking (MPPT) electronic converters are typically employed to maximise the power extracted [24]. This leads to the formation of what is called a distributed MPPT subsystem in which each TEG array's electrical operating point is controlled independently, in a similar way as for photovoltaic systems [25]. The primary motivation for this approach is that in most TEG systems the individual thermoelectric modules are subject to temperature mismatch. Examples of situations where this mismatch occurs directly include thermal variability as found in exhaust gas systems [6,26] or where the thermal conductivity of the mechanical system is poorly controlled [27]. Variability of the electro-thermal performance of individual TEG modules is also sufficient to cause a significant mismatch [28]. The mechanical clamping force the TEG is subjected to indirectly contributes to similar variation in electrical operating point, due to changes associated with the thermal contact resistance which is partially pressure dependent [29]. Consequently, when in operation each TEG in the array will have a different maximum power point. This maximum power point is the electrical operating point at which maximum energy can be extracted from the TEG. The normal operating condition for a TEG is to ensure that the load impedance is equal to (or greater) than the internal resistance, so that thermal conductance does not decrease the thermal to electrical conversion efficiency of the overall system. Ideally each TEG should be independently electronically controlled [30] but this would greatly increase the number and complexity of the MPPT power electronic converters needed and adversely affect the cost of implementing the system.

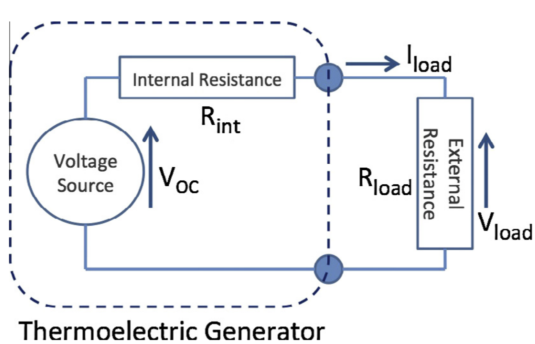

Fig. 1. Electrical model of a thermoelectric generator.

As the use of TEGs extends into progressively lower cost applications [31] the overall system economics dictate that a compromise must be found between the number of MPPT converters and the number of TEG modules connected to each converter. Problems of decreased thermal efficiency (due to parasitic Peltier effects) or decreased power output arise if the TEGs connected in the same array are subject to temperature mismatch because the MPPT converter sets the same suboptimal electrical operating point for each module in the array.

In the design of thermoelectric systems it is a key requirement to ensure that minimal temperature mismatch is applied to individual TEG devices. The aforementioned latest findings reported in the literature confirm that variable temperature distributions are commonly found in present thermoelectric systems. Some prototype systems show total performance lower than expected and sometimes thermoelectric system designers are not even aware of the effects of thermal imbalance.

However, no thorough analytical study has been undertaken to quantify the magnitude of this problem. Liang et al. [32] presented some experimental results for two TEGs electrically connected in parallel under different temperature but they focused only on showing how their theoretical model compared to real results. They did not quantify the power lost due to mismatched conditions out of the maximum power that the two TEGs would be producing if electrically loaded independently. The work we present in this article greatly extends this study and allows a quantitative assessment of the performance of interconnected TEG arrays when the elements are not all equally thermally heated. Also, the effect that non-optimal electrical operating points have on the thermal balance of each TEG is analysed.

The work presented in this article deals, for the first time in literature, with the issues related to thermally unbalanced TEGs connected in series and parallel, in a structured and rigorous way. It provides a way to predict the thermal and electrical behaviour of the system when several TEG devices are electrically connected in series or parallel, under balanced or unbalanced thermal conditions. Experimental results taken from an operating thermoelectric generating system using multiple thermally unbalanced TEGs confirm the theoretical analysis and provide a figure relative to the magnitude of power lost due to temperature mismatch. The results presented are discussed and a comparison between series and parallel connection of TEG arrays is provided, to assist in some design decisions related to thermoelectric systems. The experimental work we have conducted shows that simulation models [33] currently in use should be updated to include additional physical effects that were previously assumed not to have an impact.

2. Thermoelectric power generator device characteristic

The magnitude of the open-circuit TEG voltage is determined by the Seebeck coefficient and the magnitude of the absolute