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Validating an alternative method to predict thermoelectric generator performance

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ABSTRACT

When designing a system that utilises TEG (Thermoelectric generator) technology, it is required to know what will be the performance of the TEGs under the expected operating conditions. To do this, equations that model the performance of the TEG must be used. There are existing equations which predict the efficiency and power output of the TEGs but in this paper, alternative equations are derived which are far simpler than the existing equations to use. These derived equations predict the efficiency and maximum power output as a function of temperature difference. Parameters which describe the characteristics of the TEG such as the gradient of the current – voltage curve, gradient of the open circuit voltage – temperature difference curve and the thermal resistance are required to be able to use these equations. Testing was undertaken to find these parameters and to validate the output of these equations to the experimental results. It was found that the equations derived are valid but should not be used at very high temperature differences.

1. Introduction

TEGs (Thermoelectric generators) make use of what is known as the Seebeck effect which is explained in Fig. 1. A TEG is made up of many elements of *N* type and *P* type semiconductor material which are connected electrically in series but thermally in parallel. When there is a temperature difference over one of these elements, a small voltage is generated. The difference between the *N* and *P* type materials is the voltage generated is opposite. The total voltage of the TEG is the sum of all the voltages generated by the n and p type elements. The voltage generation means there are applications for these TEGs to generate electricity where temperature differences are present. TEGs have been proposed for industrial heat recovery [1] and car exhaust heat recovery [2] but they have the potential to be used in any application that a temperature difference is present and electrical power is required. Their efficiency is typically no higher than 5% [3] but they can generate power from any temperature difference unlike other heat engines. This is why they are typically used for low temperature difference applications. Their efficiency is limited by the Carnot efficiency so the higher the temperature difference, the more efficient they will be. A TEG operates at approximately 20% of the Carnot efficiency over a wide temperature range [4]. Heat engines operating at similar low temperature differences, such as an organic Rankine cycle engine, can have higher efficiencies reaching approximately 13% [5]. Despite their relatively low efficiency, the use of TEGs has many desirable attributes such as silence, small size, scalability and durability. Their key attribute is that they have no moving parts and no chemical reactions therefore there is little maintenance required due to wear and corrosion. The thermoelectric figure of merit (ZT) can be used to compare the efficiencies of different TEGs operating at the same temperatures. The higher the ZT, the better the TEG. The ZT of thermoelectric generators has improved over time but presently the best commercially available TEGs have a ZT of approximately 1 [4]. The most popular form of thermoelectric material is Bismuth Telluride. The use of this material in generators is limited because their maximum hot side operating temperature is relatively low. As they are widely used and mass produced, their cost is low compared to other thermoelectric materials. Other materials and techniques have been used to improve the power generation and efficiency of TEGs. Materials such as Lead Telluride and Calcium Manganese have been used in TEGs due to their ability to handle higher temperatures. Some TEGs have been manufactured with segmented material [6]. A material with a high ZT at higher temperatures is used on the hot side (i.e.: Lead Telluride) and a material with a high ZT at lower temperatures is used on the cold side (i.e.: Bismuth Telluride). More power would be produced compared to a TEG made of just the high temperature rated material. Other materials such as Skutterudites and other

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Nomenclature

I	electric current (A)
I_{SC}	TEG short circuit current (A)
m_1	gradient of the *I–V* curve (V/A)
m_2	gradient of the $V_{oc} - \Delta T$ curve (V/°C)
P	electrical power (W)
P_{max}	maximum electrical power output of the TEG (W)
$\dot{Q}$	rate of heat transfer through the TEG (W)
$R_{other\ 1}$	thermal resistance on TEG cold side (°C/W)
$R_{other\ 2}$	thermal resistance on TEG hot side (°C/W)
R_{TEG}	TEG thermal resistance (°C/W)
ΔT	TEG temperature difference (°C)
T_c	TEG cold side temperature (°K)
T_h	TEG hot side temperature (°K)
$T_{heat\ sink}$	temperature of the heat sink (°K)
$T_{heat\ source}$	temperature of the heat source (°K)
V	voltage (V)
V_{OC}	TEG open circuit voltage (V)
V_{SC}	measured TEG short circuit voltage (V)
ZT	thermoelectric figure of merit

Greek symbols

η_{th}	maximum heat to electricity conversion efficiency of the TEG (%)

manufacturing techniques such as quantum well structures have been investigated to improve TEG power generation efficiency [3,7,8] but they are still very expensive and not commercially available.

If the ZT of the TEG is known, it is possible to predict the performance of the TEG. Typically, Eq. (1) is used to predict the efficiency the TEG [2,7,9–12]. Eq. (1) can be manipulated to form Eq. (2) which predicts the power output of the TEG. These equations will be referred to as the ZT theoretical method.

$$\eta_{th} = \left(\frac{T_h - T_c}{T_h}\right) \frac{(\sqrt{ZT+1} - 1)}{(\sqrt{ZT+1} - 1) + \frac{T_c}{T_h}} \tag{1}$$

$$P_{max} = \left(\frac{T_h - T_c}{T_h}\right) \dot{Q} \frac{(\sqrt{ZT+1} - 1)}{(\sqrt{ZT+1} - 1) + \frac{T_c}{T_h}} \tag{2}$$

Eqs. (1) and (2) are known to work quite well for predicting the performance of TEGs but these equations are more complicated than required. When modeling systems making use of TEGs, the simpler the equations are, the better. Apart from the ZT of the TEG, specific hot and cold side temperatures are needed, not just temperature difference. To find the power output, the rate of heat transfer also needs to be known. Also, when testing a TEG to find ZT, it is difficult to determine ZT without at least a graphics calculator with an equation solver program. It is possible to define other equations which determine the power output and efficiency of the TEG as a function of just temperature difference. These equations are simple to derive from first principles and the parameters in the equations are simple to obtain from testing a TEG. This paper aims to validate the equations derived herein.

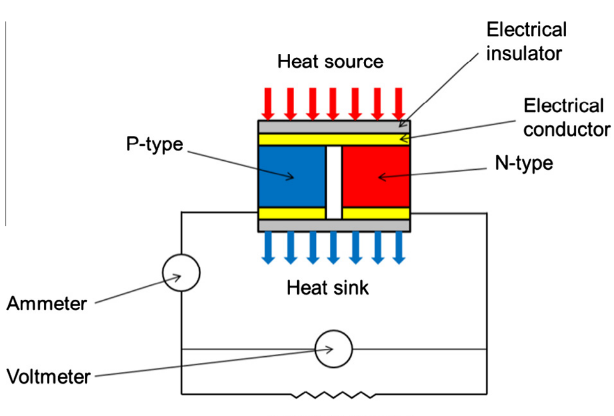

Fig. 1. Seebeck effect.

2. Derivation of the alternative power and efficiency equations

The maximum power of a TEG is generated when it operates at half the open circuit voltage. When the voltage is half the open circuit voltage, the current is at half the short circuit current [12]. Therefore, the equation for maximum power is:

$$P = VI \tag{3a}$$

$$P_{max} = \frac{1}{2} V_{oc} \times \frac{1}{2} I_{sc} \tag{3b}$$

$$P_{max} = \frac{1}{4} V_{oc} I_{sc} \tag{3c}$$

The generic *I–V* curve equation is:

$$V = m_1 I + V_{oc} \tag{4a}$$

The generic *I–V* curve is shown in Fig. 2.

When $V = 0$, $I = I_{sc}$, therefore:

$$0 = m_1 I_{sc} + V_{oc} \tag{4b}$$

$$I_{sc} = -\frac{V_{oc}}{m_1} \tag{4c}$$

Substituting Eq. (4c) into (3c) obtains the following equation:

$$P_{max} = \frac{1}{4} V_{oc} \left(-\frac{V_{oc}}{m_1}\right) \tag{5a}$$

$$P_{max} = -\frac{V_{oc}^2}{4m_1} \tag{5b}$$

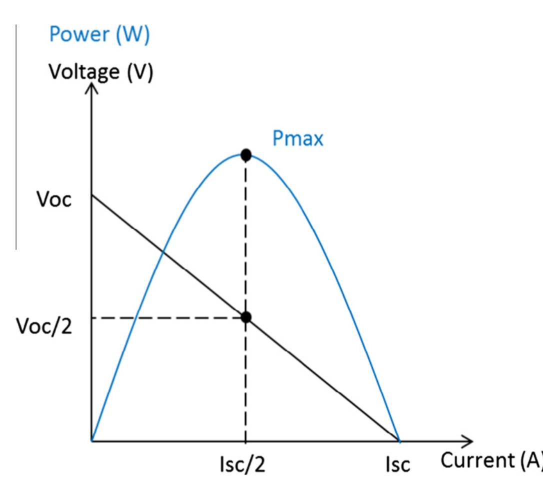

Fig. 2. The generic TEG *I–V* curve and power curve.