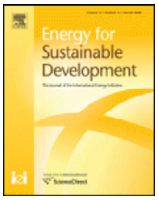
Energy for Sustainable Development 25 (2015) 8–16

Contents lists available at ScienceDirect

Energy for Sustainable Development



Evaluation of power generation from thermoelectric cooler at normal and low-temperature cooling conditions

Wei-Hsin Chen [a,*], Chen-Yeh Liao [b], Chien-Chang Wang [b], Chen-I Hung [b]

[a] Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan, ROC
[b] Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC

ARTICLE INFO

Article history:
Received 14 December 2013
Revised 16 December 2014
Accepted 16 December 2014
Available online 3 January 2015

Keywords:
Thermoelectric cooler (TEC)
Seebeck coefficient
Power generation
Numerical prediction
Low-temperature and normal cooling

ABSTRACT

Three different methods for predicting the Seebeck coefficient and power generation of a commercial available thermoelectric cooler (TEC) module are used and compared to the experimental data. Method 1 and 2 are developed based on mathematical models and Method 3 is established in terms of experimental measurements. Method 3 considers the effect of cooling condition, whereas Method 1 and 2 don't. Two different temperatures at the cold side of the TEC module are also considered to account for the influence of cooling condition on the performance of the TEC. The power generation of the TEC module with low-temperature cooling is at least 5% higher than that with normal cooling. Method 3 gives the best prediction in open circuit voltage and power generation. Basically, the three methods are able to evaluate the properties and performance of a TEC easily, thereby providing useful tools for designing and constructing a TE generation system.

Introduction

Thermoelectric coolers (TECs) are one of the coolers used for refrigeration. They are based on the Peltier effect (Gurevich and Logvinov, 2005; Meng et al., 2014a; Wang et al., 2012a; Chen et al., 2014a). When the electric power is applied, heat energy will be absorbed on one side of the TEC and dissipated on the other side so as to achieve cooling purpose. The cooling performances of commercial TECs can be evaluated by several parameters, such as the maximum temperature difference (ΔT_{max}), the maximum absorbed heat ($Q_{c,max}$), the coefficient of performance (*COP*), and the figure of merit (Z). In general, the first two parameters, ΔT_{max} and $Q_{c,max}$, of the commercial TECs are provided by manufacturers. The maximum temperature difference (ΔT_{max}) across the TEC is identified when the absorbed heat or cooling power is equal to zero, whereas the maximum absorbed heat ($Q_{c,max}$) develops when ΔT is zero. *COP* is the ratio of absorbed heat to applied electric power, and Z is defined by Ioffe (1957), Mahan (1989), Abramzon (2007) and Wang et al. (2014)

$$Z = \frac{a^2}{\rho_e} \tag{1}$$

where α, ρ_e, and k are the Seebeck coefficient (V K^{-1}), electrical resistivity (Ω m), and thermal conductivity (W m^{-1} K^{-1}), respectively. A higher value of *COP* or Z value leads to a better performance of TEC.

Compared with other coolers, TECs possess numerous benefits, such as direct electric energy conversion, compact structure without moving parts causing vibration or noise, no refrigerants, high reliability, low maintenance fee, and easy control (Simons et al., 2005; Huang et al., 2005; Wang et al., 2012b). Consequently, much research has been carried out in recent years (Wu and Hung, 2009; Martinez et al., 2011; Chen et al., 2012a). Among the related research, the concept of TECs for power generation was developed by Min and Rowe (1998). They noted that commercially available TECs could also be used to recover low-temperature waste heat and generate power but not just used for refrigeration. Waste heat can be found extensively in industrial processes (Chen et al., 2005; Chen and Syu, 2011) and no cost is required when it is reused. Therefore, TECs are a potential device to fulfill electricity generation from waste heat. Some researchers have employed TECs for thermoelectric power generation (Maneewan and Chindaruksa, 2009; Chen et al., 2012b). This conversion process by transforming heat energy into electricity is based on the Seebeck effect (Meng et al., 2014b; Meng et al., 2015; Chen et al., 2014b). The conversion efficiency of TECs is relatively low, typically around 5% (Riffat and Ma, 2003). Nevertheless, this drawback can be resolved when the heat energy comes from waste heat (Riffat and Ma, 2003; Bell, 2008). Besides, compared with TE generators (TEGs) originally designed for TE power generation,

---

* Corresponding author. Tel.: +886 6 2004456; fax: +886 6 2389940.
E-mail address: weihsinchen@gmail.com (W.-H. Chen).

http://dx.doi.org/10.1016/j.esd.2014.12.004
0973-0826/© 2014 International Energy Initiative. Published by Elsevier Inc. All rights reserved.

Nomenclature

A	cross-sectional area of thermoelectric element (m^2)
B	constant (V)
C	constant ($V\ K^{-1}$)
D	constant (depends on the used data)
COP	coefficient of performance (dimensionless)
I	electric current (A)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	length of thermoelectric element (m)
N	number of thermoelectric pairs (dimensionless)
P	power (W)
Q_c	cooling power (W)
T	temperature (°C)
T_w	temperature of water in the tank (°C)
V	voltage (V)
Z	thermoelectric figure-of-merit (K^{-1})

Greek letters

α	Seebeck coefficient ($V\ K^{-1}$)
ΔT	temperature difference across the thermoelectric module (°C)
ρ_e	electrical resistivity (Ω m)

Subscript

c	cold side
H	heating surface
h	hot side
l	load
oc	open circuit
out	output
max	maximum
w	water

TECs, which have lower cost, are more suitable to be used for low-temperature waste heat recovery (Chen et al., 2012b).

However, unlike the cooling performance, the parameters to access the power generation of TECs are hardly found in the datasheet provided by manufacturers. Therefore, several researchers have explored the procedure to obtain the interior parameters or material properties of TECs. Huang et al. (2000) utilized fully automatic testing instruments to acquire the properties of TECs. Luo (2008) presented a mathematical method to estimate the characteristics of TECs. Although the parameters obtained from the experiment are more precise than those from the mathematical method to predict the performances of TECs in a real situation, the automatic testing instruments are not accessible for users. Hence, the mathematical method presented by Luo (2008) is more feasible for users to select the appropriate TECs (Palacios et al., 2009). Similar research can be found for TEGs. Woo and Lee (2003) conducted an experiment to find the relationship between the generated voltage and temperature difference across a TEG. Hsu et al. (2011) also constructed an experimental system and proposed the concept of effective Seebeck coefficient to discuss the inconsistency between the theoretical analyses and measured results.

This study is intended to predict the performances of a TEC obtained using various mathematical models and compare with the experimental measurements. An experimental system is constructed to obtain the power generation of the TEC at certain conditions. Particular attention is paid to the performances of the TEC at two different cooling situations with one the low-temperature cooling condition ($T_w \cong 1$ °C) and the other the normal cooling condition ($T_w \cong 30$ °C). The mathematical models presented by Luo (2008) and Woo and Lee (2003) will be used to calculate the parameters and power generation of the TEC for comparison.

Methodology

Mathematical model

For TEC users, there are two simple ways to estimate the properties of TEC (Luo, 2008). When these methods are adopted, some assumptions have to be made. They include: (1) the steady state running; (2) no heat loss from convection and radiation; (3) no contact resistance; (4) the equivalent scales of p- and n-type elements in each TE pair; and (5) no temperature dependence of material properties. In addition, the hot side temperature of the TEC (T_h), the number of the TE pairs inside the TEC (N), and the length (L) and cross-area (A) of the element have to be known. A TE pair is composed of a p-type element, an n-type element, and conductors to connect the two elements, as shown in Fig. 1. Four parameters of ΔT_{max}, $Q_{c,max}$, I_{max}, and V_{max} are available in the datasheet which are used for the two methods. ΔT_{max} and $Q_{c,max}$ have been illustrated earlier; I_{max} is the electric current resulting in ΔT_{max}, and V_{max} is the voltage applied on the TEC at $I = I_{max}$ and $\Delta T = \Delta T_{max}$. Method 1 uses three parameters of ΔT_{max}, I_{max}, and V_{max} to predict the properties of the TEC as the following (Luo, 2008).

$$\alpha = \frac{1}{2N} \cdot \frac{V_{max}}{T_h} \tag{1}$$

$$\rho_e = \frac{A}{2NL} \cdot \frac{V_{max}(T_h - \Delta T_{max})}{I_{max} T_h} \tag{2}$$

$$k = \frac{L}{2NA} \cdot \frac{I_{max} V_{max}(T_h - \Delta T_{max})}{T_h \Delta T_{max}}. \tag{3}$$

Method 2 uses $Q_{c,max}$, I_{max}, and V_{max} to predict the properties of the TEC as follows (Luo, 2008).

$$\alpha = \frac{1}{N} \cdot \frac{Q_{c,max}}{I_{max}(T_h + \Delta T_{max})} \tag{4}$$

$$\rho_e = \frac{A}{NL} \cdot \frac{Q_{c,max}(T_h - \Delta T_{max})}{I_{max}^2 (T_h + \Delta T_{max})} \tag{5}$$

$$k = \frac{L}{2NA} \cdot \frac{Q_{c,max}(T_h - \Delta T_{max})}{\Delta T_{max}(T_h + \Delta T_{max})}. \tag{6}$$

After getting the material properties, the open circuit voltage and output power of the TEC for the two methods can be obtained by

$$V_{oc} = \alpha \Delta T \tag{7}$$

$$P_{out} = (\alpha \Delta T - IR)I \tag{8}$$

where R is the internal resistance of the TEC and it can be measured or calculated by the following equation

$$R = 2N\rho_e \frac{L}{A}. \tag{9}$$

The Seebeck coefficient of the TEC can also be obtained from the work of Woo and Lee (2003). Although they used the experimental results to find the relationship between the open circuit voltage (V_{oc}) and the temperature difference (ΔT), the experimental system was simpler than that in the work of Huang et al. (2000). Therefore, the work of Woo and Lee (2003) is useful for users who have simpler equipment and it is referred to as Method 3 herein. In their work, the linear