Measurement 129 (2018) 281–287

Contents lists available at ScienceDirect

Measurement

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

Method for evaluating interfacial resistances of thermoelectric devices using I-V measurement

Dong Hwan Kim[a], Cham Kim[a], Jong Tae Kim[a], Duck Ki Yoon[b], Hoyoung Kim[a,*]

[a] DGIST, 333 Techno Jungang-daero, Hyeongpung-myeon, Dalseong-gun, Daegu 42988, Republic of Korea
[b] Jeongkwan Co., 330 Suseo-ro, Yangsan 50581, Republic of Korea

ARTICLE INFO

Keywords:
Electrical contact resistance
Interfacial thermal resistance
Thermoelectric device
Power generation
Open circuit voltage
Short circuit current

ABSTRACT

Research on the methodology for predicting and analyzing the performance of a thermoelectric device (TED) can offer various possibilities for enhancing its energy conversion characteristics. In this work, the methodology to determine the electrical contact resistance and the interfacial thermal resistance of a TED was studied. Based on one-dimensional heat transfer equations of power generation mode that includes electrical contact resistance and interfacial thermal resistance, we derived explicit expressions for the open circuit voltage and the short circuit current as the limiting cases of the external electrical load. The measurements of the open circuit voltage and the short-circuit current of TED were carried out for various thermal interface materials (TIMs) between the TED and heat reservoirs under varying compressive forces. The electrical contact resistance and the interfacial thermal resistance of a TED were determined by matching the measured values of the open circuit voltage and the short circuit current of a TED to the results of the analytic model. The electrical contact resistivity of the TED tested was approximately $3 \times 10^{-9}\,\Omega\text{m}^2$, irrespective of the compressive force, the hot-side temperature, and the TIMs. The interfacial thermal resistance varied sensitively with the TIMs and decreased with the compressive forces.

1. Introduction

Thermoelectric energy conversion allows potential applications in technology for cooling various electronic devices and for generating electrical power from heat [1–4]. Although the compactness, reliability, and noiselessness of thermoelectric systems have drawn much attention for industrial implementation, their low energy conversion efficiency is a major hurdle for a wide range of applications in industry. Since the late 1980s, fruitful research activities on thermoelectric materials with high figure-of-merit values have been reported, including numerous cases involving nanoscale phenomena [5–8]. Recently, this research has been extended to thermoelectric device (TED), particularly for thermoelectric generation [9–17].

A TED, consisting of multiple thermoelectric materials and electrodes, contains a large number of interfaces. For example, they are the interface between thermoelectric material and electrode, the interface between the electrode and the insulating plate, and the interface between the external surface of TED and the external thermal reservoir. These interfaces are considered to have electrical contact resistance or interfacial thermal resistance, due to the presence of micro voids or micro gaps that interfere with the flow of electricity and heat [18,21]. Because heat and electricity flow simultaneously in TED, the thermal and electrical properties of the interfaces as well as thermoelectric material properties also affect TED performance [9–17]. Material properties for TED design and analysis can be obtained by using the test specimens, but it is not easy to obtain valid interfacial resistances of TED. In case of interfacial thermal resistance, its theoretical predictions are not easy and thus experimental measurement should be done in TED service conditions. It is widely accepted that it depends on compressive force, roughness, and temperature of the interface [21].

Lots of research have been carried out on the direct measurement of the electrical contact resistance [18,20,22–28], and the measuring method at room temperature has been established. Particularly, the method employing a potential Seebeck microprobe and DC/AC current source showed that the electrical contact resistance could be measured accurately at the soldered interface even between thermoelectric material and electrode [22,23]. The direct measurement can support very useful information for evaluating the contact resistance of an individual interface and thus it would be helpful in developing and optimizing a soldering process. However, the direct measurement may have a limitation in evaluating the contact resistance of a TED level, because the contact resistance heavily depends on how the contacts are made

---

* Corresponding author.
E-mail address: hoykim@dgist.ac.kr (H. Kim).

https://doi.org/10.1016/j.measurement.2018.07.030
Received 20 December 2017; Received in revised form 7 June 2018; Accepted 12 July 2018

between the thermoelectric pellets and the electrodes. We cannot say that all the soldering interfaces in a TED are the same as the test specimens made by simulating the TED soldering process. Furthermore, the total contact resistance of a TED should sum up the individual contact measurements but it is not practically possible to measure the contact resistances at all the soldered interfaces in a TED. For this reason, it is necessary to devise an appropriate method for evaluating the electrical contact resistance of a TED.

Conceptually, we can obtain the contact resistance of a TED by subtracting the electrical resistance of all the materials in the TED from the measured resistance of the TED. However, since the Peltier effect of thermoelectric materials changes the temperature of the TED during the electrical resistance measurement [22], it is not easy to measure accurately the electrical resistance of a TED. For this reason, there is a product catalog [29] that presents ac resistance of TED. As an indirect measurement, the electrical resistance of a TED can be obtained by comparing the performance results under specific operating conditions with those of analytic/numerical models. For example, in an ideal unit couple consisting solely of thermoelectric materials, its electrical resistance is equal to the external electrical resistance at which maximum power generation occurs [1]. However, in the numerical analysis including the interfacial resistances, the maximum power generation is observed for the external electrical load between 1.0–1.1 times of the internal resistance according to the operating conditions. As another indirect method, a study of experimental apparatus and numerical model to characterize the electrical contact resistance of a TED operated in refrigeration mode was reported [19]. They showed that the electrical contact resistance of a TED could be estimated from the relation between the TED power consumption and the TED power requirement calculated by the numerical model and that the estimated electrical contact resistivity qualitatively agreed with the measurement.

In this paper, we report a novel methodology to evaluate the electrical contact resistance and the interfacial thermal resistance in a TED using TED I-V measurements and the analytic model in power generation mode. The analytic model was devised to analyze the performance of a unit couple consisting of thermoelectric materials, electrodes, insulating plates, and several interfaces. A TED was considered as an assembly of proper numbers of these unit couples. To demonstrate the use of the methodology, current & voltage measurements of a TED were carried out in the power generation mode and the electrical contact resistance and the interfacial thermal resistance of the TED were evaluated using the measured values of open circuit voltage and short circuit current.

2. Analytic model for open-circuit voltage and short-circuit current of a unit TE couple

Based on one-dimensional heat transfer analysis, an analytic model for evaluating TED performance was developed to study the effects of the thermal and electrical resistances related to the interfacial layers that exist inside a TED and between the TED and external heat reservoirs. The mathematical formulation of the model was derived for a unit couple composed of a p-type leg, an n-type leg, the electrodes connecting the two legs, and insulating plates with external heat reservoirs, shown in Fig. 1(a). The performance of a TED is assumed to be equal to the value obtained by multiplying the performance of the unit couple by the number of couples comprising the TED.

In Fig. 1(a), each interfacial layer is assumed to have its own interfacial thermal resistance Θ, and the interface between the electrode and thermoelectric material is assumed to have an electrical contact resistivity ρ_c. In Fig. 1(b), a conceptual temperature profile is presented for power generation mode with the interfacial thermal resistances taken into account. A discontinuous temperature change is assumed at all interfaces, and a uniform temperature can be assumed in the electrode because its thermal and electrical conductivities are sufficiently high. Although the hot heat reservoir of temperature T_H and the cold heat reservoir of temperature T_C are assigned to the unit couple, the temperatures at both ends of the thermoelectric material are $T_h(<T_H)$ and $T_c(>T_C)$, respectively, because of the interfacial thermal resistances and the insulating plate.

The material properties are assumed to be constant even though they are dependent on the measured temperature, because a properly chosen value from the measured data could reduce the discrepancy that arises from the use of constant values. We now define the variables for the unit couple, such as the electric resistance of the thermoelectric materials R, the electrical resistance due to the electrical contact resistivity R_C, the thermal conductance of the thermoelectric materials K, the thermal conductance of the insulating plate K_I and the figure of merit Z, in terms of material properties and dimensions of the couple. We use ρ_p and ρ_n for the electrical resistivity of the p- and n-type thermoelectric materials, respectively. κ_p and κ_n are the thermal conductivity of the p- and n-type thermoelectric materials, respectively. S_p and S_n are the Seebeck coefficients of the p- and n-type thermoelectric materials, respectively. A and L represent the area of each leg and the length of thermoelectric material of the couple, and κ_I and L_I are the thermal conductivity and the thickness of the insulating plate, respectively. The electrical resistance of the unit couple R_t is then equal to ·. Additionally, for notational convenience, we introduce the temperature difference between the external heat reservoirs ΔT and the temperature difference in the thermoelectric material δT.

$$R = \frac{L}{A}(\rho_p + \rho_n) \tag{1}$$

$$R_C = 4\frac{\rho_C}{A} \tag{2}$$

$$\mathrm{K} = \frac{A}{L}(\kappa_p + \kappa_n) \tag{3}$$

$$K_I = \frac{2A}{L_I}\kappa_I \tag{4}$$

$$Z = \frac{(S_p - S_n)^2}{KR} \tag{5}$$

$$\Delta T = T_H - T_C \tag{6}$$

$$\delta T = T_h - T_c \tag{7}$$

The one-dimensional steady-state heat transfer equations for each thermoelectric legs with Joule heating of the generated electric current I, are as follows:

$$\kappa_p A\frac{d^2T_p}{dx^2} + I^2\frac{\rho_p}{A} = 0, \tag{8}$$

$$\kappa_n A\frac{d^2T_n}{dx^2} + I^2\frac{\rho_n}{A} = 0. \tag{9}$$

Then, the temperature distributions $T_p(x)$ and $T_n(x)$ in the p-type and n-type thermoelectric material legs, respectively, are expressed by

$$T_p(x) = T_h - (T_h - T_c)\frac{x}{L} + \frac{I^2}{2}\frac{\rho_p L^2}{\kappa_p A^2}\frac{x}{L}\left(1 - \frac{x}{L}\right), \tag{10}$$

$$T_n(x) = T_h - (T_h - T_c)\frac{x}{L} + \frac{I^2}{2}\frac{\rho_n L^2}{\kappa_n A^2}\frac{x}{L}\left(1 - \frac{x}{L}\right). \tag{11}$$

Notably, the boundary conditions $T_p(x=0) = T_n(x=0) = T_h$ and $T_p(x=L) = T_n(x=L) = T_c$ are employed even though T_c and T_h are not known yet. The total heat $Q(x)$ transferring through both the p leg and the n leg can be expressed as

$$Q(x) = I\{S_pT_p(x) - S_nT_n(x)\} + I^2(\rho_p + \rho_n)\frac{x}{A} + K\delta T - \frac{I^2R}{2}. \tag{12}$$

The electrical current I in Eqs. (10)–(12) flowing through the unit couple and an electrically connected external electrical load R_L is