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Characterization of a thermoelectric generator at low temperatures

Sevan Karabetoglu, Altug Sisman *, Z. Fatih Ozturk, Turker Sahin

Istanbul Technical University, Energy Institute, 34469 Maslak, Istanbul, Turkey

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ABSTRACT

For the low temperature applications of Bi_2Te_3 based thermoelectric power generators (TEGs), determination of low temperature material behaviors is important. In the temperature range of 100–375 K, temperature dependency of Seebeck coefficient and electrical conductivity of a Bi_2Te_3 based TEG are experimentally determined. Furthermore, for a constant temperature difference, the variation of maximum power output with the mean temperature is analytically examined based on the experimentally measured material properties. It is observed that 250 K seems a critical mean operating temperature for the considered Bi_2Te_3 module. Correlations for temperature dependency of material quantities are also given for the temperature region of 100–375 K. The results can be used for the low temperature applications of Bi_2Te_3 based TEGs.

1. Introduction

Thermoelectric devices consist of simple thermocouples which can directly convert either thermal energy into electrical energy for power generation applications or electrical energy into thermal energy for heating or cooling applications. Although thermoelectric devices have many advantages; they are not commonly used due to their lower efficiency and higher costs in comparison with those of the conventional systems. After the recent advances in material science, however, thermoelectric power generator modules with 5% efficiency and Peltier coolers with COP value of 1.5 for 20 °C temperature difference are commercially available. On the other hand, higher efficient (up to 17% for 200 °C temperature difference) TEG modules based on different type of nano-materials have been developed in many research laboratories [1–3,19].

In most of the applications, thermoelectric devices are used for cooling purposes [4–7]. However, thermoelectric generators have also been used in a number of applications such as battery charging [8], waste heat recovery [9,10], power from radioisotopes [11,12], as well as electrification of rural homes [13]. Thermoelectric devices are commonly produced for the operating temperatures ranging from room temperature to higher temperatures. Therefore, there are only a few works in literature on the characteristics and performance of thermoelectric devices at low temperature range [14–17]. Heat energy transfer from environment to the liquefied natural gas (LNG) during its evaporation can be used to generate electricity by TEGs [14]. Therefore evaporation process of liquefied gases constitutes a possibility for the low temperature applications of TEGs.

In this work, a Bi_2Te_3 based thermoelectric power generator is considered since they are commercially available and relatively inexpensive. Its material characteristics such as Seebeck coefficient and electrical conductivity are experimentally determined for low temperature region (100–300 K). Furthermore the variation of maximum electrical power output for a given temperature difference with the mean operating temperature is analyzed by using the experimentally measured material properties in some analytical expressions. The results represent the low temperature characteristics of Bi_2Te_3 based thermoelectric materials. They can be useful for the studies on low temperature engineering applications of TEG modules as well as the material science.

2. Experimental set-up

The schematic diagram of the experimental set-up is shown in Fig. 1. The set-up consists of thermoelectric module which is clamped between two copper plates contacting hot and cold surfaces. The thermoelectric module is surrounded by XPS insulator to reduce heat losses to ambient. For the measurements, temperature, heat flux, current and voltage sensors are used. Uncertainties of voltmeter, ampere meter, thermometer and heat flux meter are ±0.04%, ±1%, ±0.5% and ±3% respectively. K-type thermocouples are used for the temperature measurement of both hot and cold side lead surfaces of TEG module as well as the interfaces between the copper plates and hot and cold plates. The heat flux meters are settled between copper plates and TEG module surfaces. The system also includes the liquid nitrogen vessel at 77 K and electrical heaters to adjust the cold and hot surface temperatures, T_L and T_H respectively.

* Corresponding author. Tel.: +90 212 285 39 39; fax: +90 212 285 38 84.
E-mail addresses: karabetoglu@itu.edu.tr (S. Karabetoglu), sismanal@itu.edu.tr (A. Sisman), ozturkzeh@itu.edu.tr (Z. Fatih Ozturk), turker.sahin@gmail.com (T. Sahin).

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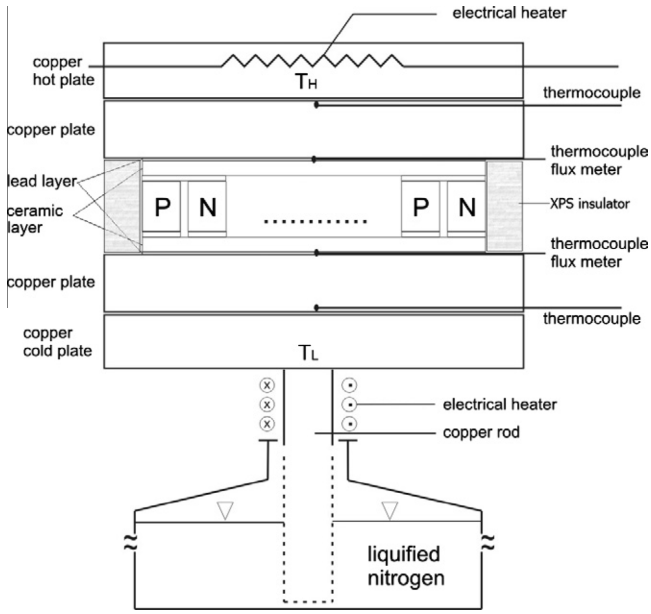

Fig. 1. Schematic diagram of the experimental set-up.

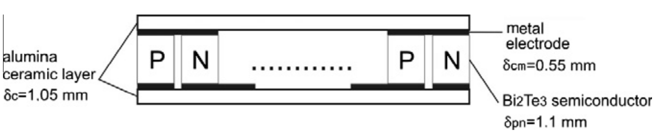

Fig. 2. Schematic cross-sectional view of TEG module.

A commercially available Bi_2Te_3 based thermoelectric generator is chosen. It generates 14.1 W electrical power for hot and cold side temperatures of 250 °C and 50 °C respectively. The overall sizes are 56 mm width, 56 mm length and 4.3 mm height (or thickness). The number of p–n semiconductor couples is N_{pn} = 241. For both p-type and n-type single semiconductors, base sizes are 1.7 mm × 1.7 mm and its thickness is 1.1 mm. The cross-sectional view as well as thicknesses of materials are seen in Fig. 2. Open circuit voltage and short circuit current are 8.4 V and 6.7 A respectively for T_L = 50 °C and T_H = 250 °C.

3. Characterization

During the experiments, the temperature difference between hot and cold surfaces of TEG module is kept constant at 20 K. For ΔT = 20 K temperature difference; generated voltage V, current I, heat fluxes at hot and cold sides ($\dot{q}''_H$ and $\dot{q}''_L$) as well as temperatures T are measured for different electrical load, R_L values practically ranging from zero to infinite ohms. The ambient temperature is set to 25 °C (298 K) and the heat exchange between ambient and the lateral walls of the generator is neglected. Because the lateral surfaces are insulated by XPS material and also the total lateral surface area is too small in comparison with hot and cold side surfaces. Measurements are repeated for different mean temperatures, $\overline{T} = (T_H + T_L)/2$, ranging from 100 K to 375 K. Since the temperature difference is small enough (ΔT = 20 K), temperature dependence of Seebeck coefficient and electrical conductivity are assumed to be linear for this small temperature interval ranging from $T_L = \overline{T} - \Delta T/2$ to $T_H = \overline{T} + \Delta T/2$. In this case, integral averages of these quantities for temperature interval of 20 K are equal to their values at mean temperature. Therefore, open circuit voltage V_o is expressed as

$$V_o = N_{pn}\int_{T_L}^{T_H} \alpha_{np}(T)dT = N_{pn}\int_{\overline{T}-\Delta T/2}^{\overline{T}+\Delta T/2} (A_\alpha + B_\alpha T)dT$$
$$= N_{pn}(A_\alpha + B_\alpha \overline{T})\Delta T = N_{pn}\alpha_{np}(\overline{T})\Delta T. \quad (1)$$

where $\alpha_{np} = \alpha_p - \alpha_n$ is the Seebeck coefficient of a single p–n couple, A_α and B_α are the linear coefficients representing the temperature dependency of the Seebeck coefficient for a small temperature interval. Therefore temperature dependent Seebeck coefficient is simply calculated by measuring the open circuit voltage and temperatures of hot and cold sides as

$$\alpha_{np}(\overline{T}) = \frac{V_o}{N_{pn}\Delta T}. \quad (2)$$

The full derivate of a material quantity (Seebeck coefficient and electrical conductivity) with respect to the measured quantities represents the uncertainty of the material quantity as a function of uncertainties of the measured quantities. By using the linear approximation (small uncertainties), the ratio of the full derivative of the material quantity to its value is assumed to be the value of total percent uncertainty. Therefore, total percent uncertainty of the Seebeck coefficient is calculated from (2) as follows

$$\frac{d\alpha}{\alpha} = \frac{dV_o}{V_o} - \frac{d\Delta T}{\Delta T}. \quad (3)$$

and

$$\Delta_\alpha = \pm\Delta_V \pm \Delta_{\Delta T}. \quad (4)$$

Uncertainty of the measurement of Seebeck coefficient is in order of ±0.54%.

Determination of internal resistance based on simultaneous DC current and voltage measurements causes wrong results since the DC current itself induces a Peltier effect which changes the temperature difference during the measurement. This induced temperature difference changes the net electrical potential difference applied to the material and causes wrong resistance measurement. Therefore to prevent the induction of Peltier effect during the measurement of internal electrical resistance, it is measured by an impedance meter, which uses AC signal. Internal resistance can be expressed as

$$R_i = N_{pn}\left[\frac{1}{\sigma_n}\frac{\delta_n}{A_n} + \frac{1}{\sigma_p}\frac{\delta_p}{A_p} + 2\frac{r_{con}}{A_{con}}\right]. \quad (5)$$

where σ is the electrical conductivity, δ is the thickness, A is the cross sectional area, r_{con} is the contact resistance between metal electrodes and semiconductor p–n couple while the subscripts n and p represent n-type and p-type semiconductors respectively. Here the resistance of metal electrode itself is neglected since the electrical conductivity of metals is too high in comparison with those of semiconductors, $\sigma_e \gg \{\sigma_n, \sigma_p\}$.

In macroscopic thermoelectric devices, electrical contact resistance between the semiconductor and metal electrodes has been reported to typically be between 10^{-8} and 10^{-9} Ω m^2 [18]. In this work, r_{con} is assumed to be 5.10^{-9} Ω m^2 as an average value. Since $\delta_n = \delta_p = \delta_{pn}$ and $A_{con} = A_n = A_p = A_{pn}$ for the considered TEG, (5) can be simplified as

$$R_i \cong N_{pn}\left(\frac{1}{\sigma_n} + \frac{1}{\sigma_p} + \frac{2r_{con}}{\delta_{pn}}\right)\frac{\delta_{pn}}{A_{pn}} = N_{pn}\left(\frac{\sigma_n + \sigma_p}{\sigma_n\sigma_p} + \frac{2r_{con}}{\delta_{pn}}\right)\frac{\delta_{pn}}{A_{pn}}$$
$$= N_{np}\left(\frac{1}{\sigma_{pn}} + \frac{2r_{con}}{\delta_{pn}}\right)\frac{\delta_{pn}}{A_{pn}}. \quad (6)$$

Therefore electrical conductivity of p–n pairs is expressed by

$$\sigma_{pn}(\overline{T}) = \frac{\sigma_n\sigma_p}{\sigma_n + \sigma_p} = \left[\frac{R_i(\overline{T})}{N_{pn}}\frac{A_{pn}}{\delta_{pn}} - \frac{2r_{con}}{\delta_{pn}}\right]^{-1}. \quad (7)$$