Module Characteristics and Performance Analysis of Thermoelectric Generators

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Abstract—**This paper presents a generalized theoretical model for predicting the module performance of a thermoelectric generator. Thermoelectric modules are solid-state devices which can transform heat into electricity because of operating following the Seebeck effect. They have several advantages such as the absence of mechanical moving parts, long operating life, and high reliability. When designing a thermoelectric generator system, the characteristics such as the resistivity, the thermal conductivity, and the Seebeck coefficient should be taken into account in order to simplify the system design. However, it may need to do the destructive experiment to determine the characteristics of the material. This paper analyses the performances of the thermoelectric generators with distinct number of semiconductor pairs under different temperature difference conditions. The results calculated by theoretical model are then compared with simulation software. All the averaged absolute errors between the theoretical model and simulation are within 6.06%.**

Index Terms—**module characteristics, thermoelectric generators and efficiency**

I. INTRODUCTION

Thermoelectric modules are solid-state devices which can transfer heat into electricity directly as coolers, based on the Peltier effect. They can also transfer electricity into heat directly as generators, based on the Seebeck effect. The applications of thermoelectric devices remained minimal until the development of semiconductor materials. [1], [2] Thermoelectric generators offer many advantages such as long operating life, compact in sizes, the absence of mechanical moving parts, and high reliability. Thermoelectric devices apply widely, have many evident advantages and significant application value.

The module characteristics of a thermoelectric module including electrical resistivity, thermal conductivity, and Seebeck coefficient have capacity to affect its performance of generating electricity. Therefore, while designing the thermoelectric systems, the module characteristics must be taken into account to simplify the design and enhance the performance of thermoelectric generator systems. [3] However, manufactures of commercial thermoelectric modules provide datasheets of the performance information under several limited conditions, but users are not known details about the parameters of internal materials. [4]

The object of this study is to calculate the module characteristics through datasheets of the performance information provided by manufactures and then develop the theoretical model by using the module characteristics. The performance analysis of the thermoelectric generator with distinct number of semiconductor pairs will be calculated through the theoretical model under different input conditions. The results of the performance calculated by the theoretical model will be compared to the that by that getting from simulation software provided by manufacturers.

II. THERMOELECTRIC EFFECTS

Thermoelectric effect is a phenomenon which can convert either temperature gradient into electricity or electricity into heat. The thermoelectric effects primarily involve the Seebeck effect (1822), the Peltier effect (1834), and the Thompson effect (1851).

A. Seebeck Effect

When two different metals connect each other, the electron diffusion will occur in order to eliminate the difference of electron density. The rate of the electron diffusion will be proportional the temperature difference between hot side and cold side. While achieving the equilibrium, there is an electromotive force between hot side and cold side, and it is the principle of thermoelectric generators. The Seebeck coefficient is defined as the ratio of the thermoelectric voltage and the temperature difference between terminals [5]:

$$s = \frac{\Delta V}{\Delta T} \tag{1}$$

where s is the Seebeck coefficient, ΔV is the thermoelectric voltage between the terminals, and ΔT is the temperature difference between the terminals.

B. Peltier Effect

When an electric current passes through a closed loop of two conductive materials with distinct properties, the

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temperature gradient will take place. The junction of two conductive materials will generate heat or absorb heat according to the direction of the electric current passes. The Peltier coefficient represents how much heat is carried per unit charge [6]:

$$\pi = \frac{I}{Q_C} \tag{2}$$

where π is the Peltier coefficient, I is the current passes through the loop, and Q_C is the heat absorbs from the cold temperature side.

The Peltier coefficient is proportional to the Seebeck coefficient as the current is constant.

$$\pi = sT \tag{3}$$

C. The Application of Thermoelectric Effects

The Seebeck effect applies to the temperature measurement by using thermocouples, and has an application potential of generating electricity. On the other hand, the Peltier effect primarily applies to cooling or heating including refrigerators, dehumidifiers, compact heat exchanger, etc.

III. Modelling and Simulation

A. The Thermoelectric Generator Modulization

Module characteristics of a thermoelectric generator can be calculated by the data sheet provided by the manufacture. The performance of a thermoelectric generators is able to predict by inputting different temperature difference. The figure of merit (Z) is an important index to estimate the capacity of the thermoelectric element. The higher value of figure of merit represents the material is more suitable for thermoelectric element, and figure of merit is defined as:

$$Z = \frac{s^2}{\rho\kappa} \tag{4}$$

where Z is the figure of merit, ρ is the electrical resistivity and κ is the thermal conductivity.

According to the above equation, the smaller value of thermal conductivity and resistivity brings to a better material for performance, and semiconductor materials satisfy such conditions. However, these parameters can only obtain through destructive experiments. To prevent destructive experiments, modelling of thermoelectric device is necessary.

Modularizing a thermoelectric generator and equation (1) can be rewritten as [7]:

$$Z = \frac{S_M^2}{R_M K_M} \tag{5}$$

$$S_M = 2Ns \tag{6}$$

$$R_M = \frac{2N\rho}{G} \tag{7}$$

$$K_M = 2NGk \tag{8}$$

where K_M is the total thermal conductivity of the generator legs, S_M is the total Seebeck coefficient, R_M is the total resistance, G is the geometry factor and N is the number of thermoelectric element pairs.

B. The Energy Equations

When a thermoelectric generator operates, it associates with four basic physical phenomena, namely the Seebeck effect, the Peltier effect, the Tomson effect and the Joule effect. Consider the contribution of these four phenomena to energy flow under steady state condition, expressed through a unit volume as follows [8]:

$$TJ\frac{da}{dx} + \tau J\frac{dT}{dx} - \rho J^2 - \frac{d}{dx}\left(\kappa\frac{dT}{dx}\right) = 0 \tag{9}$$

where T is temperature, J is current density, τ is the Thomson coefficient, ρ is the electrical resistivity and κ is the thermal conductivity of the material.

The contribution of the Thomson effect is such small that it could be neglected. The equation of the heat flows at hot junction and cold junction can be governed:

$$Q_H = K_M \cdot (T_H - T_C) + S_M \cdot T_H \cdot I - \frac{1}{2}I^2 R_M \tag{10}$$

$$Q_C = K_M \cdot (T_H - T_C) + S_M \cdot T_H \cdot I + \frac{1}{2}I^2 R_M \tag{11}$$

where Q_H is the heat receives from the hot temperature side, Q_C is the heat releases from the cold temperature side, T_H is the hot side temperature, and T_C is the cold side temperature.

Thus, the net power produced by the module (P_m) is

$$P_m = Q_H - Q_C = [S_M(T_H - T_C) - IR_M] \cdot I = V_m I \tag{12}$$

where V_m is load voltage.

The efficiency is defined as the ratio of generated electric power P_m and the heat Q_H input into the thermoelectric generator:

$$\eta = \frac{P_m}{Q_H} \tag{13}$$

where η is efficiency.

C. The Relationship between the Datasheet and Module Characteristics

For Thermoelectric generators, manufactures often provide the datasheets involving power P_m, load voltage V_m, and maximum efficiency η_{max} at match load.

The input conditions of the thermoelectric generator are cold side temperature and hot side temperature. According to the Seebeck effect, if there is a temperature difference (□ΔT) between hot side and cold side, thermoelectric generators will generate electric potential difference (V_m):

$$V_m = \frac{S_M}{2\Delta T} \tag{14}$$

$$P_m = \frac{V_m^2}{R_M} \tag{15}$$

$$\eta_{max} = \frac{T_H - T_C}{T_H}\frac{\sqrt{1+Z\bar{T}}-1}{\sqrt{1+Z\bar{T}}+\frac{T_C}{T_H}} \tag{16}$$

where $\bar{T}$ is the average temperature. Then rewrite the parameters as:

$$S_M = \frac{2V_m}{\Delta T} \tag{17}$$

$$R_M = \frac{V_m^2}{P_m} \tag{18}$$

$$K_M = \frac{[S_M(\Delta T - \eta_{\max} T_h)]^2}{[2(2-\eta_{\max})\Delta T \eta_{\max} R_M]} \tag{19}$$

Based on above formulas, the results calculated based on the above equations are compared to simulation results getting from Hi-Z, the software provided by Hi-Z Technology.

D. *The Simulation Software*

This study uses the software, TEG module performance calculator, that is provided by Hi-Z Technology. This software can not only provide the appropriate generators for user, but it can also calculate the efficiency of the thermoelectric generators under different conditions. Moreover, the user can calculate the performance of the thermoelectric modules.

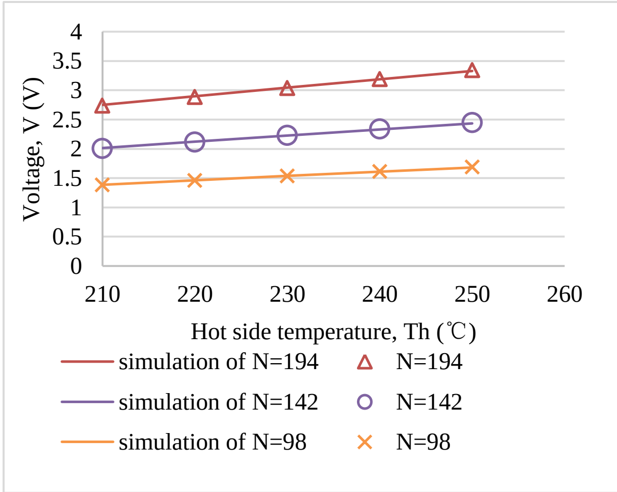
The first step of calculating the performance of the thermoelectric generator is selecting a module type or inputting the custom module parameters. The next step is inputting the operation conditions including the hot side temperature and the cold side temperature. Then, the software will calculate the performance under the input condition and provide the figure of the current-voltage curve, the load curve, and the power curve.

IV. Results and Discussion

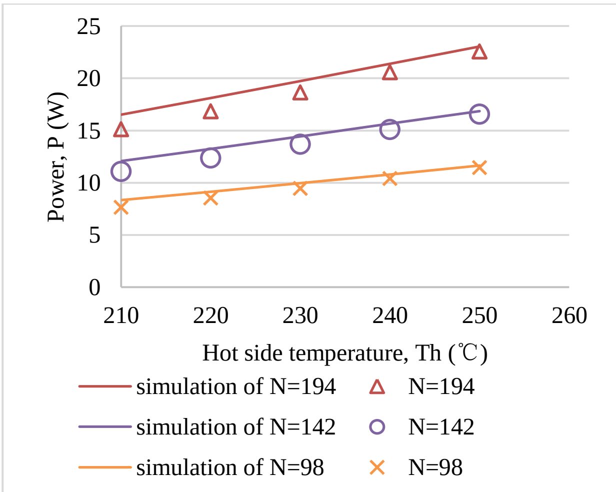
The prediction results of thermoelectric generators are shown in Fig. 1, Fig. 2 and Fig. 3. Fig. 1 shows the calculation and simulation results of the output voltage, the out power and the efficiency versus the hot side temperature of three types of thermoelectric generators at a constant TC equals to 30℃. The higher number of thermoelectric elements has lager gradient of voltage and power output as TH increases. The efficiency increases as the temperature difference increases The average absolute error percentage of Fig. 1(a) are 0.81%, 0.90%, 0.90%, that of Fig. 1(b) are 2.29%, 2.03%, 2.03%, and that of Fig. 1(c) are 4.80%, 5.07%, 5.32% for N=194, 142, 98 respectively.

Fig. 2 shows the voltage, the output power and the efficiency versus the cold side temperature of three types of thermoelectric generators at a constant TH equals to 250℃. The higher number of thermoelectric elements has lager gradient of voltage and power output as TC increases. The efficiency decreases as the temperature difference decreases The average absolute error percentage of Fig. 2(a) are 0.35%, 0.31%, 0.31%, that of Fig. 2(b) are 6.06%, 5.81%, 5.81%, and that of Fig. 2(c) are 2.50%, 2.51%, 2.51% for N=194, 142, 98 respectively.

Fig. 3 shows the voltage, the output power and the efficiency versus the cold side temperature of three types of thermoelectric generators at a constant temperature difference, which equals to 200℃. The higher cold side temperature, the voltage, the output power, and the efficiency will be lower. The higher number of thermoelectric elements has lager gradient of the power output. The voltage and the power decrease as TC increases. The average absolute error percentage of Fig. 3(a) are 0.90%, 2.03%, 5.32%, that of Fig. 3(b) are 0.31%, 5.81%, 2.51%, and that of Fig. 3(c) are 0.24%, 4.92%, 2.84% for N=194, 142, 98 respectively.



(a)



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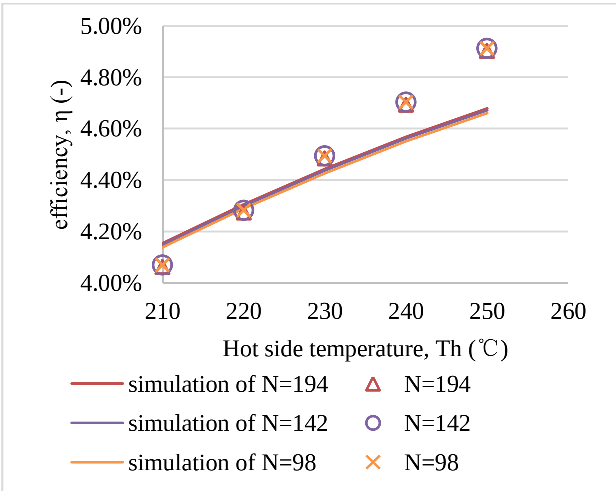
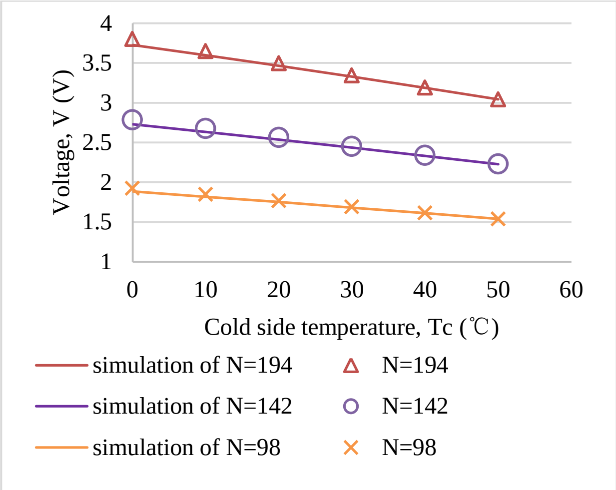
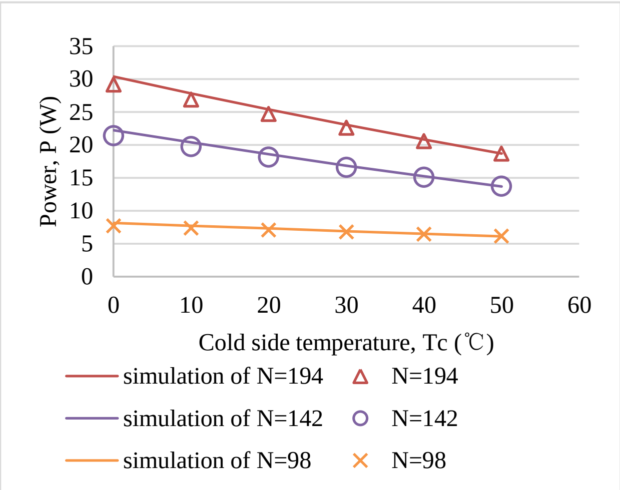


(c)

Figure 1. Performance of thermoelectric generators as hot side temperature rises at a constant cold side temperature (TC=30℃): (a) output voltage, (b) output power, (c) efficieency



(a)



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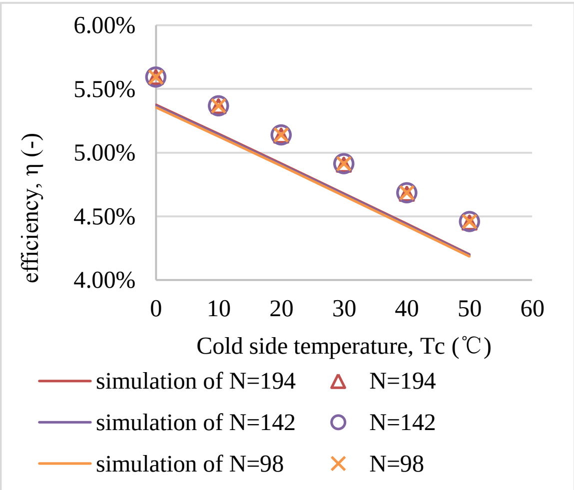
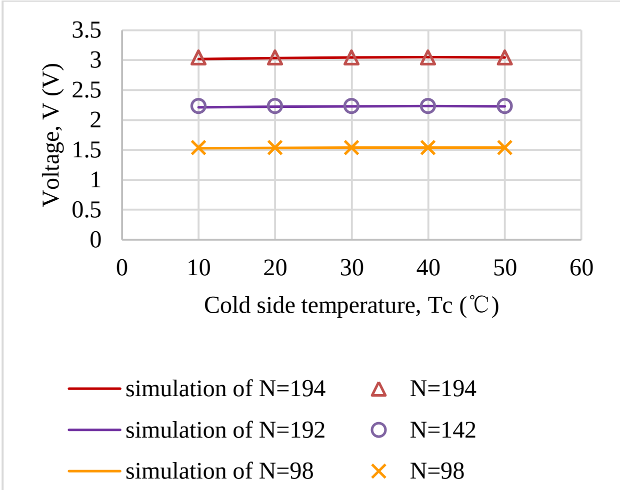
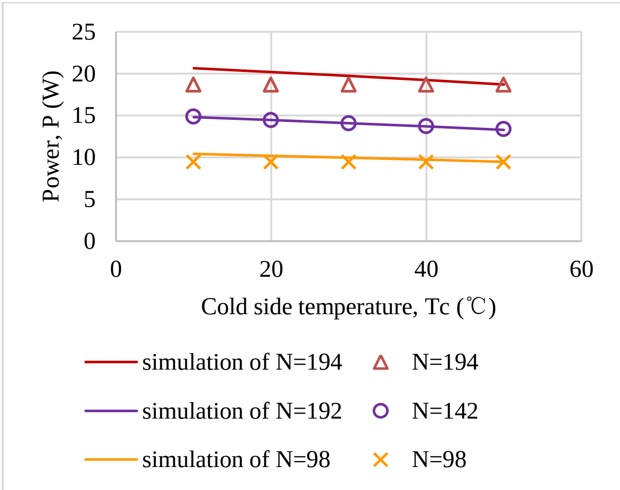


(c)

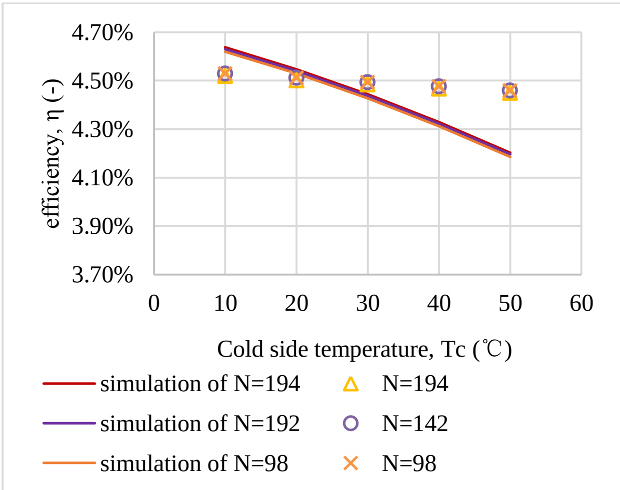
Figure 2. Performance of thermoelectric generators as cold side temperature rises at a constant hot side temperature (TH=250 ℃): (a) output voltage, (b) output power, (c) efficiency



(a)



(b)



(c)

Figure 3. Performance of thermoelectric generators as cold side temperature rises at a constant temperature difference (ΔT=250 ℃): (a) output voltage, (b) output power, (c) efficiency

V. Conclusions

In this study, the module characteristics of thermoelectric generators have been determined by utilizing the parameters shown in product catalogue, and the performances under different input conditions have been calculated and compared to the results of simulation software. The thermoelectric generator with more thermoelectric elements can have higher power output under the same temperature difference. However, there are no significant differences between their efficiencies.

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