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THE STUDY OF THERMOEMF EFFECT ON EXIT PARAMETERS OF THERMOELECTRIC MODULES

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In this study, a new method is investigated, in order to calculate all of the parameters of thermoelectric modules. Using of this new method, to determine the dynamic parameters of a real thermoelectric module in different rejimes, equations had setten up. Measuring thermoemf created by a working module is the basis of this new method. For an ideal module the parameters calculated both with classical and the new method became similar.

Keywords: Thermoemf, method, measurement, dynamic parameter, thermoelectric module

1. INTRODUCTİON

The microparameters of a semiconductor and the resistivity, Seebeck coefficient, thermal conductivity and the figure of merit of a module can be evaluated by many known methods [1-9]. By using these parameters, the thermal parameters of a module can be obtained. The classical methods, while evaluating the thermal parameters of a working module, can lead to incorrect results. Therefore there is a need in a new approach for calculating the values of a working module.

The general form of a thermal balance equotion of the cooling and warming surfaces of a thermoelectric module is given below in equation (1) [10, 11]

$$Q_C = \alpha I T_C - 0,5I^2R - K(T_H - T_C) - Q_L$$

$$Q_H = \alpha I T_H + 0,5I^2R - K(T_H - T_C) \qquad (1)$$

Where; Q_c is the total thermal load presented to the cold side in Watts, I is the current applied to the module in Amperes, R is the resistance of the thermoelement in ohms, K is the thermal conductivity of the thermoelement in W/^{o}C, α, is the total Seebeck coefficient of the thermoelement. Additionally, $\Delta T=(T_H-T_C)$ and T_H ,T_C are the thermal difference, hot side and cold side temperatures respectively. Here $Q_L= Q_{Rad}(W) + Q_{Conv}(W)$ is the total heat loads, Q_{Rad} is the radiation heat load and Q_{Conv} is the convection heat load represents total external thermal load in Watts.

The power consumed by the module is expressed as:

$$P = I^2R + \alpha\left(T_H - T_C\right)I \qquad (2)$$

One of the thermal characteristics of a thermoelectric module is the coefficient of performance-COP. COP of a thermoelectric module is expressed as the ratio of cold side heat, Q_C to the power consumption, P:

$$COP = \frac{Q_C}{P} \qquad (3)$$

The figure of merit of the module can be written as (3):

$$Z = \frac{\alpha^2}{RK} \qquad (4)$$

These equations are the basis of the classical method. For calculating the exit parameters of a module with the classical method, Seebeck coefficient, thermal conductivity and the figure of merit of a module must be obtained when the module is working. But for a working module obtaining these coefficients is very difficult. Because the exit parameters of a real thermoelectric module changes according to temperature and the geometric factor of thermoelement [12, 13, 14]. Also interface layers play important roles in thermoelectric devices [15]. To evaluate the exit parameters of the module with the classical method the heat values T_H and T_C of every thermoelements to be calculated seperatly. In this case two sensors have to be used for each thermoelement. It is also difficult to calculate the total heat loads Q_L that reaches the module by using the equations (1) - (4), because in most cases it is impossible to measure directly the cold side temperature (T_C) and the heat conductance (K) in a working module.

A new method that contains more easily measurable makro parameters was developed in this study for solving this problem. The new method is based on equations (1)-(4). But these equations are caused to become equality differences. As a result the thermal parameters of the thermoelectric modules can only be found by measuring the applied current, I and thermoelectric power, E that is produced. The current and the thermoelectric power can be measured with great sensitivity and easily.

2. METHOD

For an ideal thermoelectric module that works without load, when $Q_L = 0$ then $Q_C = 0$. Therefore the temperature difference between the hot and cold sides equals $\text{Д}T_{max}$, and the temperature of the cold side equals T_{Cmin}. In such a situation the applied current is I_{max} and voltage on the module is V_{max}. Here from [11] it is

$$V_{max} = \text{б}T_H \tag{5}$$

Whereas the maximum voltage from [16] is

$$V_{max} = I_{max}R + \text{б}\,\text{Д}T_{max} = I_{max}R + E_{max} \tag{6}$$

Here $\text{б}\,\text{Д}T_{max} = \text{б}\,(T_H - T_{Cmin}) = E_{max}$ (7)

As a result there will be

$$R = \frac{V_{max} - E_{max}}{I_{max}} \tag{8}$$

Under these conditions the thermal balance will be:

$$\text{б}I_{max}T_{Cmin} - 0,5I^2_{max}R - K\text{Д}T_{max} = 0 \tag{9}$$

Also from the formula (7)

$$T_{Cmin} = T_H - \frac{E_{max}}{\text{б}} \tag{10}$$

is found. When we put these values (8) and (10) on their places in Eq. (9)

$$\left(V_{max} - E_{max}\right)I_{max} - 0,5\left(V_{max} - E_{max}\right)I_{max} = \left(\frac{KE_{max}}{\text{б}}\right) \tag{11}$$

An equation will be obtained, from which K can be extracted as:

$$K = \frac{0,5\text{б}\left(V_{max} - E_{max}\right)I_{max}}{E_{max}} = \frac{0,5V_{max}\left(V_{max} - E_{max}\right)I_{max}}{T_H E_{max}} \tag{12}$$

If equations (8), and (12) are used in their places in Eq.1 and if we assume $Q_L = 0$, then Q_C of the module will be:

$$Q_C = \text{б}T_C I - \frac{0,5I^2\left(V_{max} - E_{max}\right)}{I_{max}} - \frac{\text{б}\text{Д}T\left(V_{max} - E_{max}\right)I_{max}}{E_{max}} \tag{13}$$

and because the thermoelectric power of the module is:

$$E = \text{б}\,\text{Д}T = \text{б}\,(T_H - T_C) \tag{14}$$

and the temperature of the cold side will be:

$$T_C = T_H - \frac{E}{\text{б}} \tag{15}$$

and from (13) and (15) the Q_C is found as:

$$Q_C = \text{б}(T_H - \frac{E}{\text{б}})I - \frac{0,5I^2\left(V_{max} - E_{max}\right)}{I_{max}} - \frac{E\left(V_{max} - E_{max}\right)I_{max}}{E_{max}} \tag{16}$$

The hot side temperature of the module is $T_{H,}$ which depends on the way of its cooling and generally is held as a fixed. The hot side temperature of the working module is always nearly equal to the temperature of the material used in the heat transfer system as a heat transporter. The value changes of the electrical current intensity I of the thermal load affect the value T_H very little. That is why we can use as the first approach formula 5 used for I_{max} in formula 16. Under this condition it can be written as:

$$Q_C = V_{max}I - \frac{0,5I^2\left(V_{max} - E_{max}\right)}{I_{max}} - \left[I + \frac{0,5\left(V_{max} - E_{max}\right)I_{max}}{E_{max}}\right]E$$

$$Q_H = V_{max}I + \frac{0,5I^2\left(V_{max} - E_{max}\right)}{I_{max}} - \frac{0,5\left(V_{max} - E_{max}\right)I_{max}E}{E_{max}} \tag{17}$$

Also the electrical input power of the module can be calculated as:

$$P = \frac{I^2\left(V_{max} - E_{max}\right)}{I_{max}} + E\,I \tag{18}$$

The COP of module will be:

$$COP = \frac{Q_C}{P} = \frac{V_{max} I - \dfrac{0,5 I^2\left(V_{max} - E_{max}\right)}{I_{max}} - \left[I + \dfrac{0,5\left(V_{max} - E_{max}\right) I_{max}}{E_{max}}\right] E}{\dfrac{I^2\left(V_{max} - E_{max}\right)}{I_{max}} + I\,E} \tag{19}$$

In addition the figure of merit of the module according to the Eqs. (5), (8), and (12) can be written as:

$$Z = \frac{V_{max} E_{max}}{0,5\left(V_{max} - E_{max}\right)^2 T_H} \tag{20}$$

It is difficult to measure the side of temperature of any surface of the module, especially in case, when the module is a part of any other thermoelectrical device. In this case one thermocouple should be placed on every side of a module and outlets of the thermocouple should be put from the outside of device. Nevertheless it is easier to measure the hot side temperature, T_H of the module, because this surface is always outside of the device.

Following from the equations (5) and (10) relation between cold and hot side's temperatures can be written as:

$$T_C = T_H\left(1 - \frac{E}{V_{max}}\right) \tag{21}$$

According to this formula we can find the cooling surface temperature T_C, not measuring it directly, but by measuring at any time only T_H and E.

The heat equations (8), (12), (13), (17) and (23) give all of the parameters any time during the operation of the module works. In order to use these equations the values I_{max}, V_{max} and E_{max} have to be found. These values are different for each module and can be named the experimental parameters of the module. Also to use these equations we have to measure one of the temperature values -T_C or T_H- directly. Here V_{max} and E_{max} characterize the semiconductor materials of the thermoelement that are used to build the module. They are not related to the geometric factor of thermoelement and they form the macro size of the module. These values can be easily measured with a large sensitivity.

The formulas (17) – (21) express the thermal exit parameters of a working thermo element or a thermoelectric module. The analytic expressions $Q_C = Q_C(I,E)$, $Q_H = Q_C(I,E)$, $P = P(I,E)$, $COP = COP(I,E)$, $T_C = T_C(I,E)$ of the functions will change according to the applied current and the working regime of the module.

3. DISCUSSICONS

To prove that the formulas (17) – (21) are equivalent to the equations (1) - (4) we have each of thermal parameters of an ideal isolated module to be calculated with these formulas and the results should be compared. To achieve this, there can be taken a thermoelement where $K = 36.10^{-3}$ W / °C, $Z = 1,8.\ 10^{-3}/$ °C, $\sigma = 380$ µV / °C, and which is made of semiconductors that have equal resistivities with $\rho = (1/900)$ cmΩ and a size of $h = 0,4$ cm, $a = 0,5$ cm^2 and $R = 2\rho h/A = 0,00222\Omega$. Before calculating the parameters of the module, we obtain the exit parameters like V_{max}, E_{max} and I_{max} of the module in the T_{Cmin} working regime. For an ideal module, if $Q_C = 0$ and $I = I_{max}$, then $T_C = T_{Cmin}$. Also according to [16]:

$$T_{Cmin} = \frac{\sqrt{1 + 2ZT_H} - 1}{Z} \tag{23}$$

Table 1

Working Regime	According to Basic (1) - (4) Equations						
	Qc,W	Q_H,W	P,W	COP	T_C,°C	ΔT,°C	10^{-3}Z / °C
T_{Cmin}, $E = E_{max}$, $Q_C = 0$	0	4,47	4,47	0	-35	51	1,8
Qcmax, $T_C = T_H$, E = 0	2,63	6,31	3,68	0,7	16	0	1,8
	According to Gotten Equations (1) - (4)						
	Qc,W	Q_H,W	P,W	COP	T_C,°C	E,V	10^{-3}Z / °C
T_{Cmin}, $E = E_{max}$, $Q_C = 0$	0	4,47	4,47	0	-35	0,01938	1,8
Qcmax, $T_C = T_H$, E = 0	2,63	6,31	3,68	0,7	16	0	1,8

Because the hot side temperature of the modules is 16^0C or $T_H = 273 + 16 = 289$K, T_{Cmin} will be $T_{Cmin} = 238$K or be $-35\ ^0$C. From here ДТ $_{max}$ = 51 will be found. At this point according to (5), (7), (8), (12) and (20) values such as V_{max} = б T_H = 0,10982V, E_{max} = б ДТ $_{max}$ = 0,01938V, $I_{max} = (V_{max} - E_{max}) / R$ = 40,7 A , K = 36.10^{-3} W / ºC and Z = $1,8.10^{-3}$ / ºC are gotten. Also accorging to (21) when T_{Cmin} = 238K or $-35\ ^0$C ДТ $_{max}$ = 51 will be obtained Q_{Cmax} = 2,63W will be found. It is seem the values K and Z of the used semiconductors have come out the same, as obtained by calculation and two methods give the same results for both - T_{Cmin} and ДТ $_{max}$ as well.

First we have calculated all of parameters of an ideal module $Q_C = 0$, $I = I_{max}$, $T_C = T_{Cmin}$ and $T_C = T_H$, ДТ = 0, E = б ДТ = 0, $Q_C = Q_{Cmax}$ in two different working regimes by using the formulas (1) - (4) and (17) – (21). The results of the calculations are shown in Table 1.

From this table, it is seem that the results obtained from the equations (1) - (4) are the same as the results of the formulas (17) – (21). In other words (1) - (4) and (17) – (21) equal to one another. In Fig. 1we can see graphics of dependence of thermal parameters, obtained by formulas (17) – (21) for an ideal thermoelectric module working in two different regimes and different currents from thermoelectric power.

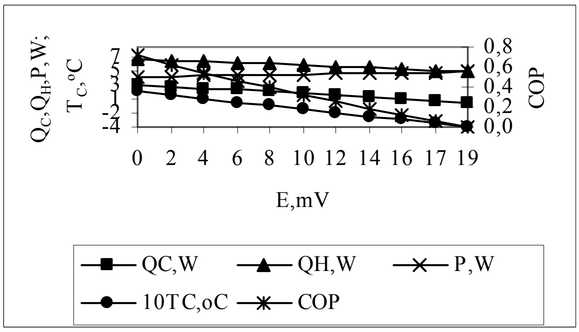

Figure 1. The change of the exit parameters for $I=I_{max}$ according to thermoemf Here, as an example, graphics are shown for $I = I_{max}$ = 40,7A.

The values that are on the E = 0 axis express the working regime of Q_{Cmax} for the thermoelement, the values that are on the $E = E_{max}$ axis show the values of the working regime of $T_C = T_{Cmin}$. As it can be seen, in the working regime Q_{Cmax}: E = 0, $Q_C = Q_{Cmax}$, $Q_H = Q_{Hmax}$, $P = P_{min}$, $COP = COP_{max}$ and $T_C = T_H$, but in the working regime T_{Cmin}: $E = E_{max}$, $Q_C = 0$, $Q_H = Q_{Hmin}$, $P = P_{max}$, COP = 0, $T_C = T_{Cmin}$ and $Q_{Hmin} = P_{max}$. Also as it is seen in the graphics, when the current intensity gets weak, the value of COP increases. Of course the results are valid not only for the given example but also for all currents.In Fig. 2 the curves of the functions I = 10A, 20A, 30A and $I = I_{max}$ = 40,7A for $Q_C = Q_C$ (E), $T_C = T_C$ (E) are shown.As it is seen in Fig. 2 in the T_{Cmin} working regime Q_C (E) the points of the curves that intersect with the E axis give the E^I_{max} value of the module of 10A, 20A, 30A and 40,7A. Also in the Q_{Cmax} working regim Q_C (E) the points of the intersection with Q_C show the Q^I_{Cmax} value that has a maximum cooling power of the module at 10A, 20A, 30A and 40,7A.

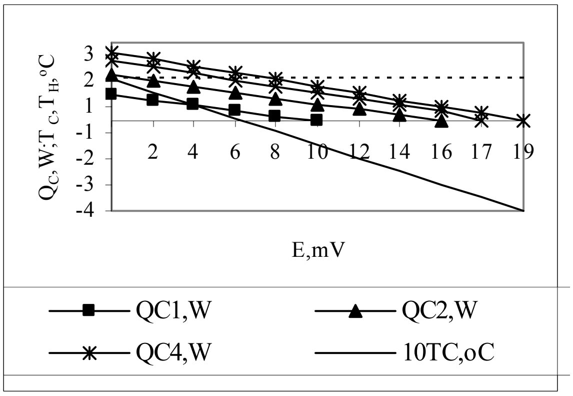

Figure 2. The thermal load for a thermoelectric module and the change of t_c according to the thermoemf

Also because the curves Q_C (E) and T_C (E) in Fig. 2 are linear, we can make use of these curves or of these analytical formulas and we can measure the thermal load and the temperature of cooling surface by measuring the thermoelectric power of a module that works under any working regimes. Similarly, the linear functions $Q_H = Q_H$ (E), P = P (E) and COP = COP (E) can be used to obtain all of the parameters of a working module.

4. CONCLUSION

The classic approach is based on using the static parameters of the semiconductors and the new one is based on using the dynamic parameters of the thermoelement and both of them are based on the same principles. For an ideal thermoelement, the theoretic formulas that were obtained according to both approaches lead to absolutely identical results that prove their total equivalence. But the situation changes, if we talk of a working module. The results obtained by using the early approach are much more exaggerated, while the values that are calculated with the new formulas are closer to real values. Also the new method makes it possible to investigate the factors which affect the work of thermoelement.

In order to investigate the dynamic thermal and electric features of a module, it is enough to measure the supplied current, I, and the voltage of a working module, V, the thermoelectric power, E, that the module produces and the temperature of any surface of the module. These measures are very simple and can be done with large accuracy. The cost of this method is very low. Also the obtained formulas characterize the dynamic parameters of a working module and they can be used for evaluataion the constructional methods, applied in production of thermoelectric devices.

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