LTspice-model of Thermoelectric Peltier-Seebeck Element

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LTspice-model of Thermoelectric Peltier-Seebeck Element

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Abstract **– A simple, symmetric, convertible into electric generator mode LTspice-model of Peltier-Seebeck element is proposed. The model parameters are extracted from the experimental measurement results of the electrical and thermal characteristics of the real elements.**

Keywords — Thermoelectric cooler (TEC), Thermoelectric generator (TEG), Peltier effect, Seebeck effect, Thermoelectric equivalence, SPICE, LTspice, model.

I. INTRODUCTION

During the electric current flows in a non-uniform electric circuit, there are possible the situations when energy in some circuit paths absorbs, and in other – generates. Traditionally relies, that the energy absorption corresponds to the positive sign, and generation to the negative sign. A value and a sign of power $P_i=U_i{\cdot}I_i$ for individual path of circuit are determined by multiplying of voltage U and current I.

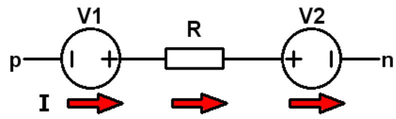

Fig. 1. Electric circuit with two Peltier's contacts and internal resistance.

The simplest Peltier circuit consists of 3 elements: two voltage sources V1, V2 and an active resistance as it can be seen in Fig. 1. A general current I flows in a circuit, so that in each of the elements generates power: $P_{V1}=-V_1{\cdot}I$; $P_{V2}=V_2{\cdot}I$; $P_R=R{\cdot}I^2$. Here, we take into account, that for element V1 the sign of the voltage drop is opposite to the sign of Electromotive force (EMF): $-U_1=-V_1$, and for an active resistance $U_R=I{\cdot}R$.

Such detail consideration of the obvious rations is important for understanding the processes of the heat redistribution in electric circuits, particularly in circuits with contact potential difference. In case if all energy conversions in electric circuit in Fig.1 connected with heat energy, then element V1 will absorb energy from surroundings and cool down, while element V2 will generate energy and heat, and element R will produce a Joule heating and heat too. In case if EMF (contact potential difference) of elements V1 and V2 are similar, and a power from active resistance R a lot less then power from V1 and V2, then will be carried a heat junction from element V1 to element V2. This junction is called a Peltier effect. Peltier effect used in thermoelectric coolers – TEC. The opposite effect – the electricity generation, due to temperature difference is known as the Seebeck effect and is used in thermoelectric generators - TEG.

Theoretical basis of thermoelectric converters viewed in details in [1-4].

There are a few interesting SPICE models of the Thermoelectric Peltier Element [2-4]. Significant disadvantages of these models are insufficient clarity and non-symmetric structure of the electric schemes, which make difficult an understanding about physical essence of thermoelectric phenomena. On the other hand, lack of physical transparency of existing SPICE-models makes it difficult to transfer and adapt to the interpretation of the extended range.

Particularly, in [5] suggests that the processes of heat redistribution take place in photoelectric solar panels, which is demonstrated in so-called "Hot spots" [6].

II. MODEL OF PELTIER-SEEBECK DEVICE

Heat output that flows from cold to hot part of the element defined by the equation

$$P_Q = \Pi{\cdot}I \tag{1}$$

where Π represents Peltier coefficient (has dimension of voltage and complies to effective contact potential difference), and I represents current. Equation (1) can be represented in the form of the balance equation of the thermal power, which generates on cold and hot sides of the element.

$$P_Q = P_c = -P_h = \left(P_c - P_h\right)/2 \tag{2}$$

Here $P_{c,h}=\pm\Pi{\cdot}I$, and the sign is determined by direction of contact potential difference relatively to current.

Equation (3) represents EMF, which generates by temperature difference on two sides of the element.

$$V_S = \alpha\cdot\left(T_h - T_c\right) \tag{3}$$

where $T_{h,c}$ - temperature of parts, α - Seebek coefficient.

Thompson equation connects Peltier coefficient and Seebeck coefficient through absolute temperature.

$$\Pi = \alpha{\cdot}T \tag{4}$$

While we design Peltier element with two voltage sources with different polarity, with contact Peltier voltages, which determined through the temperature of parts

$$\Pi_{c,h} = \alpha{\cdot}T_{c,h} \tag{5}$$

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we can make an equal description of Peltier and Seebeck effects.

Truly, heat flux from cold side to hot side transforms to

$$P_Q = (P_c - P_h)/2 = \alpha \cdot I \cdot (T_c + T_h)/2 \qquad (6)$$

here $\alpha \cdot (T_c + T_h)/2$ – average value of Peltier coefficient for two contacts (signs of power flux for different parts are opposite).

Electromotive force for two opposite switched contacts will be determined by temperature difference.

$$V_S = V_h + V_c = \alpha \cdot T_h - \alpha \cdot T_h = \alpha \cdot (T_h - T_c) \qquad (7)$$

According to the above was developed LTspice-model [7] of the Peltier element as it can be seen in Fig.2.

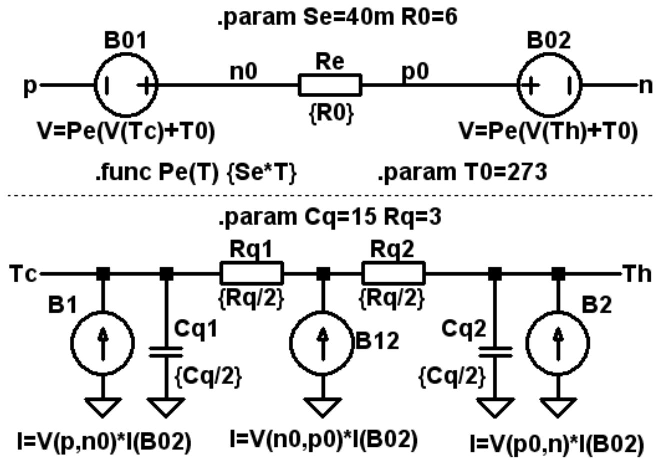

Fig. 2. Proposed LTspice-model of Peltier–Seebeck element.

The proposed model consists of electrical and thermal parts. In a thermal part of the model, current is an analog of thermal power, and a voltage is a temperature analog.

Top part of the scheme describes electric part of the model, bottom – thermal part.

Electrical contact B01, switched in reverse to the direction of current, absorbs a heat, while on contact B02, in straight direction, same heat is generated. It means that the heat transfers from cold contact to hot.

That heat described as Peltier potential coefficient – Pe. This coefficient calculated by the next SPICE function

$$\text{.func Pe}(\mathrm{T})\{\mathrm{Se*T}\} \qquad (8)$$

Here, Se represents the Seebek coefficient, and T – absolute temperature. To convert from the Celsius scale into the absolute temperature, used constant T0=273.

Joule heating generates when current flows through resistance on the element Re. Rq elements modeling an internal thermal resistance. Current sources B1, B2, B12 comply with the thermal power sources. These powers are calculating through the voltage drop on each element, with the same current for all elements.

$$P_i = U_i \cdot I \qquad (9)$$

For description of dynamic characteristics of Peltier element should consider its heat capacity.

Heat capacity of the element is described by two capacitors Cq1 and Cq2, which complies to the both sides of the element.

Model's numerical values of parameters were matched to real manufactured Peltier element (Thermoelectric cooler). Parameters of specific elements with mark TEC1-12706 get the next values:

$$\mathrm{Se} = 40\mathrm{m};\ \mathrm{R0} = 6;\ \mathrm{Rq} = 3;\ \mathrm{Cq} = 15. \qquad (10)$$

Unfortunately, electrical and thermal parameters of specific elements differ from datasheet parameters [8], but that's why they are more interesting.

III. Measured Characteristics Of Peltier-Seebeck Element

Sizes of Peltier element (mark TEC1-12706) is 40mm*40mm*3.9mm, which mean nearly 6A current at a voltage 12V, resistance nearly 2Ω, cooling power nearly 50W, and a temperature difference between cold side (isolated) and hot side (with the temperature 25°C) nearly 70°C, according to the datasheet [8].

Real characteristics of the purchased elements were much worse. First of all, the real resistance of the element was nearly 6Ω. According to this, the maximum current was less than three times and three times less was the cooling power and the temperature difference.

Temperature of the element hot side was kept near to the temperature of surrounding air, with the massive aluminum heat sink and air fan (from the computer cooling system).

Temperature of the heat sink was nearly 23°C, with a surrounding air temperature nearly 20°C.

Temperature contact between element and a hot surface was ensured by a thin layer of thermal grease with a thermal conduction 0.7W/(K*m). The cold side of the element was isolated from surrounding air with a foam plastic packaging.

Temperature was measured by a thermocouple. Temperature of the cold side was measured by a thermocouple pressed to the midpoint of the surface. Temperature of the heat sink was measured inside the 1mm diameter and 10mm depth cylindrical bore. Bore was made parallel to the effective surface area in the 3mm depth. Effective surface area sizes is 67mm*77mm. Peltier element was situated in the centre of the heat sink, and pressed to its surface with the foamed plastic overlay and screws.

On Fig.3 can be seen experimental temperature depending of the cold side of the element and the heat sink temperature on the hot side of the element, depending on surrounding air temperature.

Minimum temperature of the cold part nearly -3°C, reached at voltage diapason 10V-12V. While temperature of the heat sink increases to 25°C, ambient temperature is nearly 21°C

Having more effective cooling of the heat sink might be expected temperature nearly -10°C for the voltage nearly 15V (bottom line on Fig.3).

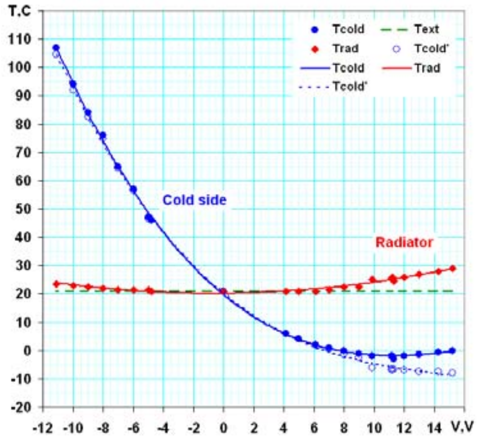

Fig. 3. Measured Voltage dependences of Temperatures for Cold side and Heat sink located on the Hot side of TEC.

On Fig.4 can be seen dynamic dependence of temperature variations of conditionally cold part versus time.

The upper curve complies with conditions of opposite polarity of the voltage source. The cold side at first is heating, and then is cooling down. The lower curve complies with conditions of direct polarity. The cold side at first is cooling down, then goes back to the surroundings temperature. Recovering of the element temperature, after heating (cooling), was carried out with power off (zero current on element).

Source voltage in experiment was 11.1V. Surrounding air temperature was 20°C.

During heating, temperature of conditionally cold part increased to 110°C, and during cooling dropped to -4°C. Time constant of temperature variation during heating and cooling ranges from 15 to 30 seconds. Thus the larger values of the time constant complies with the heating, while smaller – with cooling.

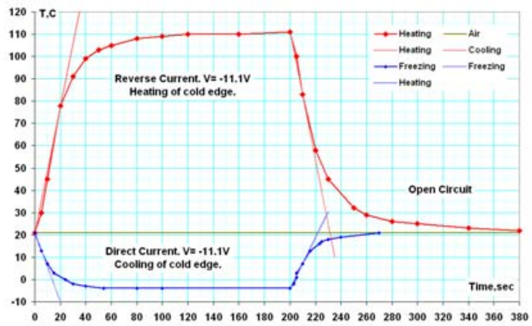

Fig. 4. Measured Time dependences of Temperature for TEC Cold side. The direct (Cooling) and reverse (Heating) modes are presented.

The research of Peltier element in the electric generator mode was carried out by setting preliminary temperature level value in a heat pump mode. Then the supply voltage was shut off. And two different situations are considered: the voltage of open circuit – OC, and the current of circuit – SC. Of course some observational error was occurred. It was caused by temperature variation of conditionally cold side during the measuring. Nevertheless, these results are interesting, because they help to decrease uncertainty in selecting of parameters of the model.

TABLE I. MEASURED PELTIER-SEEBECK TEG CHARACTERISTICS

Tcold,°C	Trad,°C	Tenv,°C	U_{OC}, V	I_{SC}, A
-2	24	21	1.0	0.15
110	25	21	-3.2	-0.46

Table I shows next values: Tcold – temperature of the conditionally cold part, Trad – temperature of heat sink, Tenv – temperature of surrounding area, U_{OC} – open circuit voltage, I_{SC} – Short circuit current.

These data can directly estimate the value of the Seebeck coefficient - about 40mV/K, and the electrical resistance in the generator mode - about 6Ω.

Described characteristics formed the basis for estimating the parameters of the model of the Peltier element.

IV. SIMULATION AND MODEL'S PARAMETERS ADJUSTMENT

To investigate the influence of the numerical values of the parameters of the Peltier element to its characteristics was collected LTspice-model experimental setup - Fig.5.

The top part of the model, with the label "Current", refers to the electric part. The bottom part, with the label "Heat" relates to the thermal part. The arrows show the direction of current and heat in normal mode of element operation.

Model of the element has two groups of terminals: electrical terminals with labels "p" – positive, and "n" – negative; thermal terminals with labels "Tc" – cold part, and "Th" – hot part.

The electrical part of the model is powered by a voltage source V1.

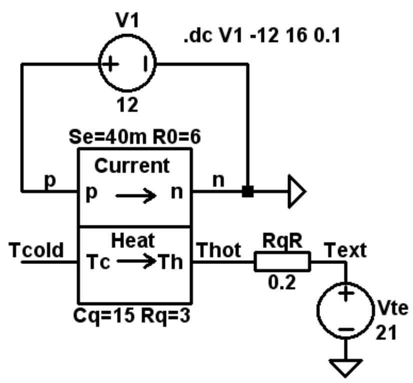

Fig. 5. LTspice-model of experimental TEC setup.

In the thermal part of the model surroundings is represented by the source temperature Vte. Heat exchange of heat sink with surroundings represented by resistor RqR. The specific value of thermal resistance is RqR=0.2, was selected by the ratio between the heat sink temperature and the surroundings. During the simulation, was assumed, that thermal resistance between hot surface of the element and the heat sink would be equal zero. The cold side of the element was isolated from the surroundings (infinite resistance or break – Open Circuit).

Fig.6 shows the results of modeling dependences the surface temperatures of the (Peltier) element on the supply voltage.

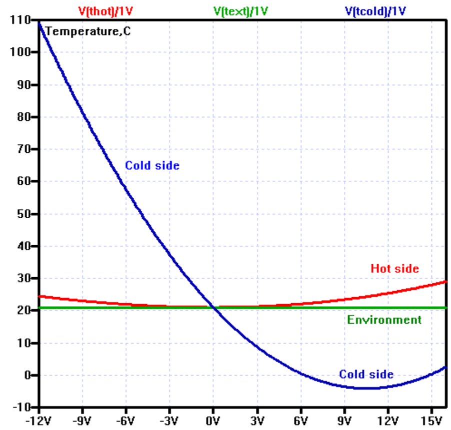

Fig. 6. Simulated Voltage dependences of Temperatures for Cold and Hot sides of TEC.

In calculations were used the next parameters of the model: Se=40m; R0=6; Rq=3; Cq=15; RqR=0.2.

In direct connection (voltage greater than zero), the temperature of the cold side is lower than the temperature of the hot side. In the reverse connection – temperature of the conditionally cold part becomes higher than temperature of the conditionally hot part. As in the experiment, the temperature of the heat sink increases with increasing voltage, regardless of the polarity. In the normal mode, the heat sink temperature is slightly higher due to the additional heat from the cold side.

Fig.7 shows the dependence of the temperature of the Peltier element, if it corresponds to the electrical resistance of its manufacturer's datasheet to TEC1-12706[8].

The graph (Fig.7) shows that if the electrical resistance of the element would be 2Ω, instead of 6Ω, the minimum temperature of the cold part would be -37°C, instead of -4°C. Naturally, a decrease of the electrical resistance could be accompanied by a decrease in thermal resistance (Fig.8).

Changing the internal thermal resistance from the nominal value Rq = 3, two times more or two times less, significantly changed the minimum temperature value, and shifts the position of the minimum temperature to voltage.

To investigate the operation of the Peltier element in the electric generator mode can be used the following scheme (Fig.9).

A voltage sources VtC and VtH complies the temperature sources on the cold and hot sides of the element. The resistor R1 produces an electrical load of the generator. A small value of the load - 1mΩ, corresponds to a Short Circuit mode, large - 1KΩ, - to idling or Open Circuit mode. The calculation results are summarized in Table II.

TABLE II. SIMULATED PELTIER-SEEBECK TEG CHARACTERISTICS

Tcold, °C	Thot, °C	U_{OC}, V	I_{SC}, A
-4	23	1.1	0.18
110	23	-3.5	-0.58

These data naturally match the specified parameters of the model: Se = 40mV/K; R0 = 6Ω.

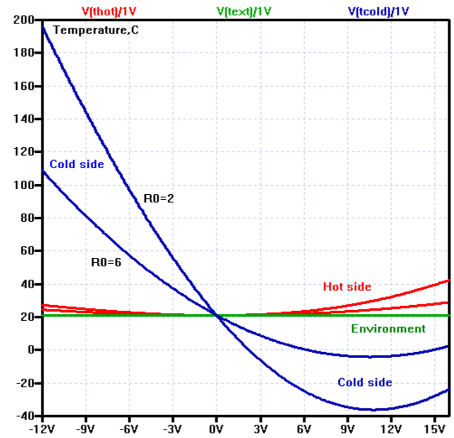

Fig. 7. Simulated Voltage dependences of Temperatures for Cold and Hot sides for several values of TEC internal electrical resistance.

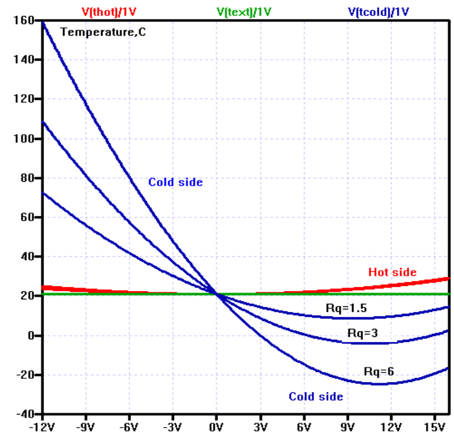

Fig. 8. Simulated Voltage dependences of Temperatures for Cold and Hot sides for several values of TEC internal heat resistance.

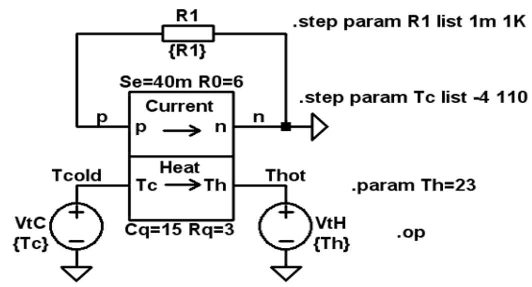

Fig. 9. LTspice-model of experimental TEG setup.

To study the dynamic characteristics of the Peltier element was assembled model shown in Fig.10.

In order to bring the model to the experimental conditions, the scheme was more complicated as to the original scheme. The voltage source Vsw controls switch SW, opening the power supply circuit element V1.

In Fig.11 can be seen the results of calculating the dependences of the temperature conditionally hot and cold sides versus time. Group of lower curves on Fig.11

corresponds to the temperature of the cold side of the element in the normal power supply +12V (cooling mode).

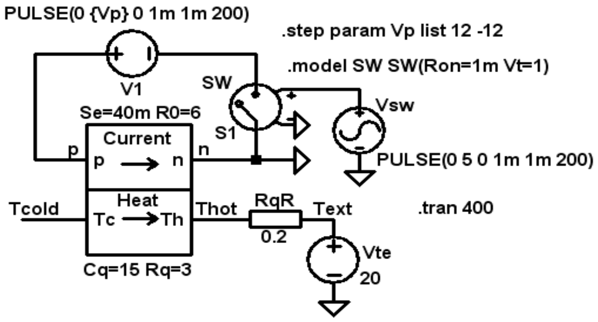

Fig. 10. LTspice-model of experimental TEC setup for dynamic tests.

Group of upper curves corresponds to the temperature of the conditionally cold side in reverse mode -12V (heating mode).

Group of curves in the middle corresponds to the temperature of the hot side of the element.

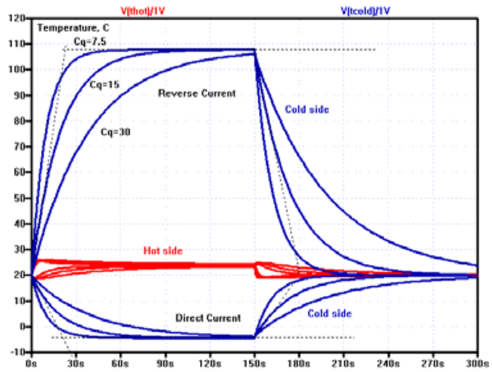

Fig. 11. Simulated Time dependences of Temperature for TEC Cold and Hot sides. The direct (Cooling) and reverse (Heating) modes are presented.

An each group contains dependency to a nominal specific heat element Cq=15, for the values in two times bigger and two times less of the nominal value.

The time constant of the temperature change in the cooling mode (heating) for the nominal values of the heat capacity is about 20 seconds.

In the mode, when the temperature of the cold side returns to the temperature of surroundings without flowing current, time constant is increased to 30 seconds.

Control calculations with shorted terminals (V=0) demonstrate the effect of the current flow influence on temperature recovering speed.

V. Conclusions

The symmetrical, interconvertible LTspice-model of the Peltier element, which converts electricity into the heat and heat into the electricity, was developed.

Model of the Peltier element is described by a small set of parameters, such as: the Seebeck coefficient, electrical resistance, thermal resistance, heat capacity. The model parameters are chosen based on the results of experimental measurements.

It is advisable to modify the model to include a number of unit cells and for electric-heat Q-factor. This allows relatively easy to change settings for other types of Peltier elements.

The developed model can be useful both in the calculation of the cooling systems for electric and thermoelectric generator, and in the educational process to illustrate the work principles of the thermoelectric elements.

Appendix SPICE Netlist

```
* PeltierTest3.asc
Vte Text 0 21
V1 p 0 12
RqR Text Thot 0.2
XX1 p 0 Tcold Thot peltier params: Se=40m R0=6 Cq=15 Rq=3

* block symbol definitions
.subckt peltier p n Tc Th
* -------- Current -----------
B01 n0 p V=Pe(V(Tc)+T0)
B02 p0 n V=Pe(V(Th)+T0)
Re n0 p0 {R0}
* --------- Heat ---------------
B1 0 Tc I=V(p,n0)*I(B02)
B2 0 Th I=V(p0,n)*I(B02)
B12 0 N001 I=V(n0,p0)*I(B02)
Rq1 N001 Tc {Rq/2}
Rq2 Th N001 {Rq/2}
Cq1 Tc 0 {Cq/2}
Cq2 Th 0 {Cq/2}
* --- params & function ---
.param Se=40m R0=6
.param Cq=15 Rq=3
.func Pe(T) {Se*T}
.param T0=273
.ends peltier

.dc V1 -12 16 0.1
.backanno
.end
```

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