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# Thermoelectric generation of current – theoretical and experimental analysis

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**Abstract** This paper provides some information about thermoelectric technology. Some new materials with improved figures of merit are presented. These materials in Peltier modules make it possible to generate electric current thanks to a temperature difference. The paper indicates possible applications of thermoelectric modules as interesting tools for using various waste heat sources. Some zero-dimensional equations describing the conditions of electric power generation are given. Also, operating parameters of Peltier modules, such as voltage and electric current, are analyzed. The paper shows chosen characteristics of power generation parameters. Then, an experimental stand for ongoing research and experimental measurements are described. The authors consider the resistance of a receiver placed in the electric circuit with thermoelectric elements. Finally, both the analysis of experimental results and conclusions drawn from theoretical findings are presented. Voltage generation of about 1.5 to 2.5 V for the temperature difference from 65 to 85 K was observed when a bismuth telluride thermoelectric couple (traditionally used in cooling technology) was used.

**Keywords:** Thermoelectric generator; Waste heat sources; Efficiency; Thermoelectrics; Renewable heat sources

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## Nomenclature

$I$ – DC current, A
$\bar{T}$ – mean temperature of thermo element
$T_c$ – temperature of the lower heat source (surroundings), K
$T_h$ – temperature of the upper heat source (waste or renewable source), K
$Q_c$ – capacity of upper heat source, W
$R$ – resistance of the thermoelement, Ω
$R_L$ – load resistance, Ω
$v$ – voltage, V
$W$ – electrical power, W
$Z\overline{T}$ – figure of merit

### Greek symbols

$\alpha$ – Seebeck coefficient, V/K
$\lambda$ – thermal conductivity, W/(m K)
$\rho$ – resistivity, Ω m
$\eta_{\max\ t}$ – thermodynamic efficiency

## 1 Introduction

Cost-effective methods of energy management are important and ways to improve energy efficiency of thermal processes are crucial in industrial and commercial applications [1]. Some ways of using waste heat sources are known, such as absorption and adsorption technologies [2,3]. Currently, thermoelectrics is one of the latest technologies recognized in many applications. Thermoelectric modules use the Seebeck effect, i.e., generation of electric current between two positive-type and negative-type semiconductor welds at various temperatures; this is a reverse effect to the Peltier cooling effect. Thermoelements can be considered an alternative source of electricity using waste exhaust heat produced in industrial (power plants, steel mills, heat sources in a variety of manufacturing industries) and commercial applications (car exhaust, gas furnaces for space heating). They could work in satellites where phase change materials (PCM) are a source of energy. What is more, renewable energy heat sources are currently considered as a driving force for thermoelectric generation. There are two main sources: geothermal and solar thermal energy. For solar applications, flat and concentrating solar thermal technologies, solar ponds, and evacuated tube heat pipe solar collectors are used. In aeronautical technology, thermoelectric modules are used to produce electricity by means of solar energy accumulated in PCMs [4]. It should be underlined that energy is widely used in heating, ventilation, air conditioning ans refrigeration (HVAC&R)

systems in buildings, too. There are problems to solve related to good and cost-effective energy flow [5,6]. Modern and wise use of fuels and renewable energy sources in buildings is where electricity generation based on a temperature difference could be taken into account as a future technology.

## 2 Thermoelectrics – properites and materials

The main advantages of electric current generation by thermoelements are the following [7]:

- The lack of refrigerant and lubricating oil, which puts thermoelectric devices in a series of future-oriented solutions for protection of the environment.
- The lack of moving parts contributes to operating cost savings related to time required for repair and maintenance (a broken thermocouple can be exchanged for a new one in short time).
- Possibility to maintain a constant operating temperature of thermocouples with a small deviation of ±0.1 K.
- Possibility to adjust the range of cooling capacity between 0 and 100%.
- A simple, maintenance-free structure.
- Possible different shapes of thermocouples – they may take the form required for a particular application.
- Possibility of cooling only the selected area or component of a device or machine.
- Operation without noise emission.
- Possible operation in conditions of weightlessness and at high load, which is important in military and space applications.

Traditional bismuth telluride thermocouples have the following main disadvantages and limitations:

- Bismuth and tellurium form toxic alloys.
- Heat losses associated with the Joule effect (heating of a semiconductor, which is connected with conduction of electric current) are observed.

- A small figure of merit $Z$ gives small thermal efficiency of electric power generation.

One definition of the figure of merit $Z\overline{T}$ is presented below, where $\bar{T}$ is mean temperature of a thermoelement (Lee 2010):

$$Z\overline{T} = \frac{\alpha^2}{\rho\lambda}\bar{T} \ . \tag{1}$$

A good thermoelectric material should have a high Seebeck coefficient to obtain high voltage. At the same time, high electrical conductivity and low thermal conductivity to limit heat loss at the joint are needed [8].

Traditional materials [9], such as bismuth telluride, $Bi_2Te_3$, have at ambient temperature (approx. 300 K) the $Z\overline{T}$ coefficient of approximately 1. Material engineering seeks to develop new materials with a better $Z\overline{T}$ coefficient, allowing to increase the area of application and improve the efficiency of electric current generation [10].

Modern thermoelectric materials are based on elements from the 4th group of the Mendeleev periodic table. Mainly, these are alloys composed of germanium and silicon ($Si_{0,8}Ge_{0,2}$ p-type and n-type). Their optimal temperature range of operation is from 870 K to 1300 K. The $Z\overline{T}$ coefficient is about 1.3. Other materials include magnesium silicide $Mg_2Si$, germanium magnesium $Mg_2Ge$, and magnesium stannate $Mg_2Sn$ [11,12] with the $Z\overline{T}$ coefficient at a level of 0.8. In addition, materials based on lead telluride doped with lanthanum and chromium [13] are currently enjoying a growing interest. Their $Z\overline{T}$ coefficient is 2.2 in 550 K and 1.8 in 850 K.

There are other materials, such as polycrystalline glass PGEC (phonon-glass electron-crystal). They have a crystalline structure forming a network with doped metal atoms. Semiconductors $Sr_8Ga_{16}Ge_{30}$ with the $Z\overline{T}$ coefficient of 1.35 (at 900 K) are the examples. Other examples include $Ba_{0,08}Yb_{0,09}Co_4Sb_{12}$ and $Ba_{0,3}Ni_{0,05}Co_{3,95}Sb_{12}$ compounds with the $Z\overline{T}$ coefficient equal to about 1.7 at a temperature of around 850 K.

The latest materials have been developed by the use of modern material science techniques [14]. For instance, there are compounds such as $AgPb_{18}SbTe_{20}$(LAST) and $(GeTe)_{75}(AgSbTe_2)_{25}$(TAGS-75) with the $Z\overline{T}$ coefficient of 1.7 at the temperature range from 700 to 800 K.

## 3 Theory

A thermoelectric generator produces electric power that is obtained on the outside receiver of the electric resistance, R$_L$, [15], it is defined as in formula:

$$W = I^2 R_L\ . \tag{2}$$

The electric current generated depends on thermoelectric properties of the material, the temperature difference between the upper and lower sources, and the resistance of the receiver, as in formula

$$I = \frac{\alpha(T_h - T_c)}{R_L + R}\ . \tag{3}$$

The thermodynamic analysis of the efficiency of the conversion of thermal energy into electricity indicates that the maximum value of the efficiency depends on the temperature of the upper and lower heat sources and the $Z\overline{T}$ coefficient, as shown in formula:

$$\eta_{\max t} = \left(1 - \frac{T_c}{T_h}\right) \frac{(1 + Z\overline{T})^{\frac{1}{2}} - 1}{(1 + Z\overline{T})^{\frac{1}{2}} + \frac{T_c}{T_h}}\ , \tag{4}$$

where $\overline{T} = \frac{(T_h + T_c)}{2}$.

Table 1 lists some possible values of the maximum generation efficiency for fixed upper and lower source temperatures.

Table 1: Estimated thermodynamic efficiency of electric power generation.

| $T_c$ | $T_h$ | $Z$ | $Z\overline{T}$ | $1 - \frac{T_c}{T_h}$ | $\eta_{\max t}$ |
|---|---|---|---|---|---|
| 300 | 550 | 0.0015 | 0.64 | 0.45 | 0.15 |
| 300 | 550 | 0.0030 | 1.27 | 0.45 | 0.25 |
| 300 | 550 | 0.0064 | 2.72 | 0.45 | 0.37 |

The values presented in table confirm that high-quality thermoelectric materials with high temperatures of the upper source are capable of delivering electrical current generation with the efficiency from 20% to 30%, making it economically acceptable.

Further theoretical analysis can determine the current and voltage of the electric current and the electric power generated that can be referenced to a possible maximum thermoelectric effect as a function of thermoelectric material properties and the receiver resistance in the electrical system:

$$\frac{\dot{W}}{\dot{W}_{\max}} = \frac{4\frac{R_L}{R}}{\left(\frac{R_L}{R}+1\right)^2}\,, \tag{5}$$

$$\frac{I}{I_{\max}} = \frac{1}{\frac{R_L}{R}+1}\,, \tag{6}$$

$$\frac{V}{V_{\max}} = \frac{\frac{R_L}{R}}{\frac{R_L}{R}+1}\,. \tag{7}$$

Graphs of these values as a function of the resistance of the receiver to the resistance of the thermoelectric material depending on the temperature of the upper and lower heat sources (given in Tab. 1) are provided below in Fig. 1.

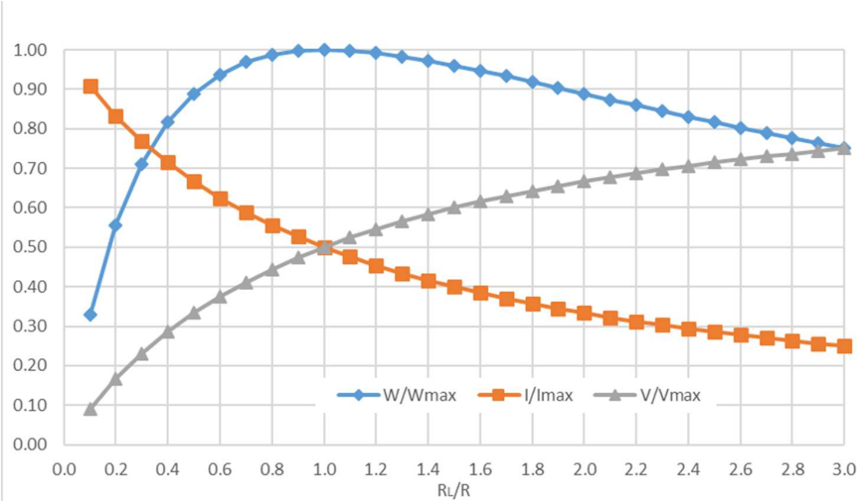

Figure 1: Dimensionless generation of electrical power (W/Wmax), current (I/Imax) and voltage (V/Vmax).

A simultaneous loss of power and current can be observed with an increasing ratio of the resistance of the receiver to the resistance of the thermoelectric material when the value of this ratio is significantly higher than 1. Thus, a thermoelectric generator with high efficiency is one that operates with a receiver with comparable resistance in the range of 50 to 150% with respect to the resistance of the thermoelement generating electrical power. For a higher resistance of the receiver, electrical power decreases with a simultaneous voltage increase. Since the efficiency of the thermoelectric generator is lower in comparison with conventional devices, it is important to select materials properly to match the generator voltage and current. Otherwise, improper selection of these parameters significantly reduces the economic efficiency of the project.

## 4 Experimental setup

An experimental stand is used to examine generation of electrical power due to heat load. The main component of the experimental stand is a Peltier thermoelement mounted between two heat exchangers (the heat exchanger with hot water flowing simulates the waste (upper) heat source, while the heat exchanger with cooling water simulates the lower heat source). The Peltier element is insulated with mineral wool. Water is preheated in a buffer tank, then pumped through a band resistance heater to obtain a desirable temperature. Next, the hot water flows through hot-side heat exchanger and returns to the buffer tank. Cooling water is prepared in an ultrathermostat and flows through a cold-side heat exchanger (Fig. 2).

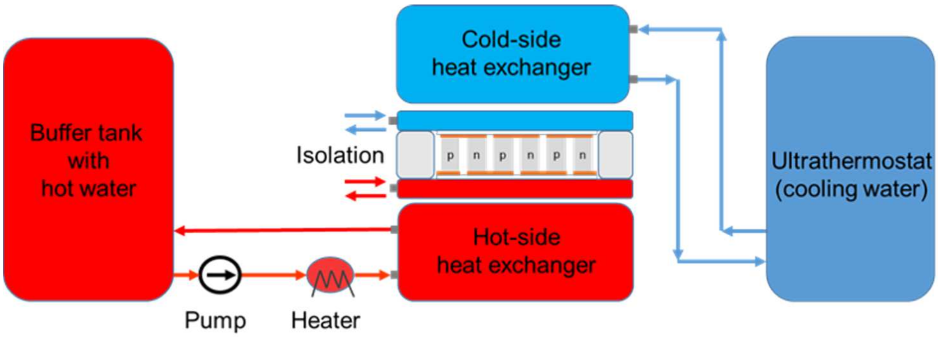

Figure 2: The scheme of experimental setup.

The study is conducted with three Peltier modules based on bismuth telluride, a traditional thermoelectric material. Tradenames of the modules are TEC1-12715, TEC1-12710, and TEC1-12708. Basic technical data are given below in Tab. 2.

Table 2: Technical data of thermoelectric modules.

| Module | TEC1-12715 | TEC1-12710 | TEC1-12708 |
|---|---|---|---|
| $T_h$ [K] | 323.0 | 323.0 | 323.0 |
| $\Delta T_{max}$ [K] | 79.0 | 79.0 | 75.0 |
| $U_{max}$ [V] | 17.2 | 17.2 | 17.5 |
| $I_{max}$ [A] | 15.0 | 10.1 | 8.4 |
| $Q_c$ [W] | 164.2 | 110.5 | 79.0 |
| $R$ [Ω] | 0.79–0.98 | 1.27–1.49 | $\sim 1.80$ |

Measurements are performed via a measurement electronic card, and data are recorded in the personal computer memory. A series of measurements with the three thermoelements was performed. Basic measurement parameters were: temperature of the hot water inlet/outlet in/from the hot heat exchanger, temperature of the cooling water inlet/outlet in/from the cold heat exchanger, electric current, and voltage in the electric circuit (Fig. 3).

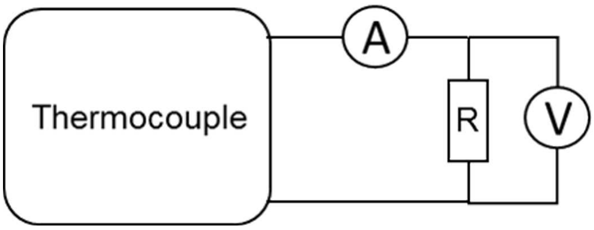

Figure 3: The scheme of measurement electric circuit.

During the experimental work, water temperature drops across both heat exchangers, thermal power supplied to the thermocouple, and electric power output on the receiver were also obtained. Table 3 shows selected measurement data and computing values gathered from the TEC1-12715 module examination. Based on the measurements, it was possible to draw voltage characteristics of thermomodules depending on the temperature difference between the upper and lower heat sources (Fig. 4).

Preliminary research results show that the level of voltage generated is similar to values obtained by other authors [16]. Getting a very small

Table 3: Selected results of the measurement and calculation for the TEC1-12715 module.

| $T_{hot}$ [K] | $\Delta T$ [K] | $I$ [$\mu$A] | $U$ [V] | $W$ [mW] |
|---|---|---|---|---|
| 335.06 | 69.07 | 333 | 1.55 | 0.516 |
| 335.25 | 69.35 | 334 | 1.56 | 0.521 |
| 335.44 | 69.57 | 342 | 1.60 | 0.547 |
| 335.69 | 69.88 | 339 | 1.58 | 0.536 |
| 336.38 | 70.50 | 340 | 1.59 | 0.541 |
| 336.50 | 70.69 | 340 | 1.59 | 0.541 |
| 336.69 | 70.95 | 342 | 1.60 | 0.547 |
| 336.88 | 71.17 | 343 | 1.60 | 0.549 |
| 337.12 | 71.44 | 345 | 1.61 | 0.555 |
| 337.31 | 71.69 | 348 | 1.63 | 0.567 |
| 337.56 | 71.94 | 356 | 1.67 | 0.595 |
| 338.37 | 72.75 | 360 | 1.69 | 0.608 |
| 339.12 | 73.50 | 363 | 1.70 | 0.617 |
| 339.81 | 74.22 | 366 | 1.72 | 0.630 |
| 340.50 | 74.91 | 370 | 1.73 | 0.640 |
| 341.19 | 75.56 | 373 | 1.75 | 0.653 |
| 341.81 | 76.22 | 376 | 1.77 | 0.666 |
| 342.50 | 76.94 | 380 | 1.78 | 0.676 |
| 343.12 | 77.56 | 374 | 1.75 | 0.655 |

value of electric current is an issue and it results in a minimum electric power generation. The reason for this is too high load resistance used. Hence, a very important conclusion can be drawn: to produce current from thermoelectric modules, a circuit with small resistance should be used or the energy should be stored properly. Otherwise, a low efficiency of power generation is observed. Besides, the operation with a small $\Delta T$ (from 60 to 80 K) near ambient temperature results in a low thermal conversion efficiency. That is why necessary modifications should be made to both the experimental setup and the way the experiments are carried out.

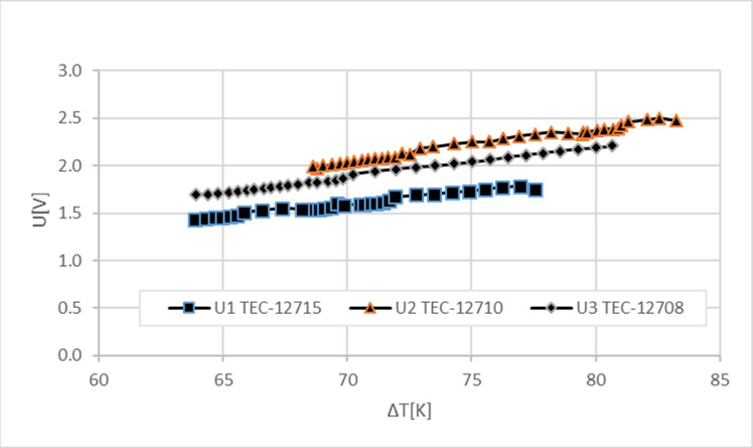

Figure 4: Voltage characteristics of Peltier modules as a function of the temperature difference.

## 5 Conclusions

The paper describes the application of Peltier thermomodules for electric current generation. For generating electric energy, either waste heat or renewable energy sources are used. Materials used at present and those of the future were listed. Basic mathematical relations were shown, and effectiveness of electric energy generation was analyzed. An experimental setup as well as the way of performing measurements and interpreting their results were described. The results of the experimental work indicate directions of future research, i.e., using materials with a better $Z\overline{T}$ coefficient and increasing the temperature difference between the 'hot' and the 'cold' sides of a thermoelement. What is more, new heat sources should be sought. It is possible to state that the issues mentioned in the paper are topical at the time and still in the research and development phase.

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