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Theoretical and Experimental Analysis of Thermoelectric Power Generation

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Abstract

This paper deals with thermoelectric technology. Selected new semiconductors with improved figures of merit are presented. Peltier modules are used to generate electric current through temperature difference. The paper indicates applications of thermoelectric modules, as interesting tools for various waste heat recovery. There are zero dimension equations describing the conditions of electric power generation including voltage and current with characteristics of the above parameters. The authors are also interested in the efficiency of electric current generation. The experimental stand, ongoing research and experimental measurements are described. The authors explore the resistance of the receiver placed in the electric circuit with thermoelectric elements. Finally, the experimental results are analyzed and theoretical conclusions made. Voltage generation of about 1.5 to 2.5 V was observed in the range of temperature difference ΔT from 65 to 85K. Measurements were taken from a bismuth telluride thermoelectric couple, which is traditionally used in cooling technology.

Keywords: thermoelectric modules, electric power generation, new semicondustors, waste heat recovery, figure of merit, efficiency

1 Introduction

Cost-effective energy management and improving the energy efficiency of thermal processes are crucial in industrial and commercial applications. Measures to use waste heat sources like absorption and adsorption technology are well-known [1]; [2]. An upcoming technology in the field is thermoelectrics, with multiple potential applications. Thermoelectric modules use the Seebeck effect: the generation of an electric current between two positive-type and negative-type semiconductor welds at various temperatures – the "reverse" effect to the cooling Peltier effect. It is possible to consider thermoelements as an alternative source of electricity generation, harnessing the waste heat produced in industry (power plants, steel mills, heat sources in manufacturing industries) and elsewhere (car exhaust, gas boilers for domestic heating). They could work in satellites where PCM material is an accumulative source of energy. Moreover, renewable energy heat sources are considered a driven force for thermoelectric generation. There are two main sorts applicable: geothermal and solar thermal energy. Solar applications include: flat and concentrated panel thermal concentration, solar ponds and evacuated tube heat pipe solar collectors. In aeronautical technology thermoelectric modules are used to produce electricity through the use of solar energy accumulated in PCM materials [3]. It should be underlined that there is a wide range of energy usage in HVAC&R systems in buildings too. There are problems to solve connected with good and cost-effective energy flow [4]; [5]. Modern and smart use of fuels and renewable energy sources in buildings is a rich area of research.

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2 Thermoelectrics – properties and materials

The main advantages of generating electric current with semiconductors are [6]:

- No refrigerant or lubricating oil required, which positions the thermoelectric device among future-oriented solutions for environmental protection;
- No moving parts, which contributes to operating cost savings related to down time for repair and maintenance (a broken thermoelectric module is quickly exchanged for a new one);
- Simple, maintenance-free structure;
- Thermoelectric modules maintain a constant operating temperature with a small deviation ± 0.1K;
- Cooling capacity can be adjusted from 0 to 100%;
- Modules require no particular shape – they may take the form required for a particular application;
- Option to cooling only a selected area or component of the device;

- No noise pollution;
- Can work in weightlessness and at high load, important in space and military applications.

The main disadvantages of traditional bismuth telluride semiconductors are:

- Toxicity of bismuth and tellurium;
- Heat losses observed associated with the Joule effect (electric current conduction heats the semiconductors);
- Small figure of merit Z gives low thermal efficiency of electric power generation

The above figure of merit could be described as [7]:

$$ZT = \frac{\alpha^2}{\rho\lambda}T$$

Semiconductors with a high Seebeck coefficient provide high voltage. At the same time high electric conductivity and low thermal conductivity are needed to limit heat loss at the joint [8].

Traditional materials [9] like bismuth telluride Bi_2Te_3 at ambient temperature (approx. 300 K) has a ZT coefficient of approximately 1. Material engineering aims to develop new materials with a better ZT coefficient in order to increase the area of application and improve the efficiency of electricity generation [10].

Modern thermoelectric materials are based on elements from the 4th group of the Mendeleev periodic table. Mainly, they 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 870K -1300K. The ZT coefficient is about 1.3. Additionally, there are magnesium silicide Mg_2Si, germanium magnesium Mg_2Ge and magnesium stannate Mg_2Sn [11]; [12], whose ZT coefficient is 0.8. There is also growing interest in materials using lead telluride doped with lanthanum and chromium [13]. Their ZT coefficient is 2.2 at 550 K and 1.8 at 850 K.

There are other materials like polycrystalline glass PGEC (Phonon-Glass-Electron-Crystal). They have a crystalline structure forming network with doped metal atoms. The semiconductors $Sr_8Ga_{16}Ge_{30}$ with a ZT coefficient of 1.35 (at 900K) are good examples. Other examples are $Ba_{0,08}Yb_{0,09}Co_4Sb_{12}$ and $Ba_{0,3}Ni_{0,05}Co_{3,95}Sb_{12}$ - compounds with a ZT coefficient of approximately 1.7 at a temperature of around 850K

The latest materials are created through developments in modern materials science [14]. For example, there are compounds such as $AgPb_{18}SbTe_{20}$(LAST) and $(GeTe)_{75}(AgSbTe_2)_{25}$(TAGS-75) with a ZT coefficient of 1.7 in the temperature range 700 - 800K.

3 Theory

A thermoelectric generator produces electrical power and it is obtained at outside load resistance R_L [7]. It is defined as in equation (2):

$$P = I^2 R_L \quad [W]$$

where: P – electrical power, I – DC current, R_L – load resistance

Generated electric current depends on the thermoelectric properties of the material and the temperature difference between the upper and lower source and the load resistance, as in equation (3):

$$I = \frac{\alpha\left(T_h - T_c\right)}{R_L + R} \quad [A]$$

where: T_h – temperature of upper heat source (waste or renewable source), T_c – temperature of low heat source (surroundings), R – resistance of thermoelement.

Thermodynamic analysis of a conversion efficiency of thermal energy into electricity indicates that maximum efficiency depends on the temperature of the upper and lower heat sources and the ZT coefficient, as shown in equation (4):

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

where:

$$\overline{Z} = \frac{(T_h + T_c)}{2}$$

In Table 1 there are some possible values of maximum efficiency generation for fixed levels of upper and lower source temperature ($T_{av} = (T_h+T_c)/2$). The values presented above confirm that thermoelec-

T_c [K]	T_h [K]	Z	ZT_{av}	$1-T_c/T_h$	max,t
300	550	0.0	0.64	0.45	0.15
300	550	0.0	1.27	0.45	0.25
300	550	0.01	2.72	0.45	0.37

Table 1: The estimated thermodynamic efficiency of electric power generation

tric materials of high quality with high temperatures of the upper source are capable of delivering electrical current generation with efficiency of 20 - 30%, making it economically acceptable.

Further theoretical analysis can determine the characteristics of the current and voltage of electric current and the generated electric power that can be referenced to the possible maximum thermoelectric effect as a function of thermoelectric material properties and receiver resistance in the electrical system. The equations for these are (5), (6) and (7).

$$\frac{W}{W_{\max}} = \frac{4\frac{R_L}{R}}{\left(\frac{R_L}{R}+1\right)^2}$$

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

$$\frac{V}{V_{\max}} = \frac{\frac{R_L}{R}}{\frac{R_L}{R}+1}$$

Fig. 1 below plots these values as a function of the resistance of receiver to the resistance of thermoelectric material depending on the temperature of the upper and lower heat source (given in Table 1).

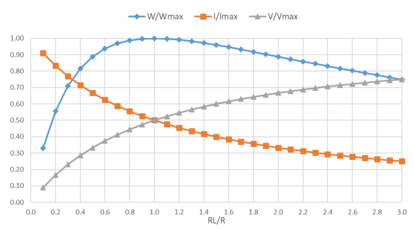

Figure 1: Dimensionless functions of the Peltier thermogenerator's operating parameters

It can be seen that there is a simultaneous loss of power and current with increasing resistance against 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 works with the receiver with comparable resistance in the range of 50 to 150% to the resistance of thermoelement generating electric power. For higher resistance of the receiver, electric power decreases with simultaneous voltage increase. Since the thermoelectric generator is less efficient than conventional devices, it is important to select materials properly and set the optimum generator voltage and electric current. Poor selection of these parameters will significantly impact the economic basis of the project.

4 Experimental setup

The experimental stand is used to examine the generation of electric power through heat load (Fig. 2). The main components of the examination stand are: Peltier thermoelement mounted between two heat exchangers (the heat exchanger with hot water flowing simulates the waste (upper) heat source, the heat exchanger with cooling water simulates the lower heat source). The Peltier element is insulated with mineral wool. The water is preheated in a buffer tank, then pumped through the band resistance heater to obtain the desired temperature. Next, the hot water flows through the heat exchanger and returns to the buffer tank. The cooling water is prepared in the ultrathermostat and flows through the cold heat exchanger.

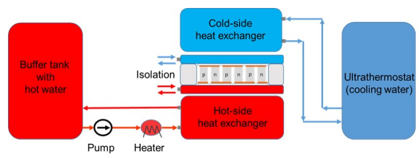

Figure 2: Schematic diagram of the experimental setup

The study is conducted with three Peltier modules fabricated with bismuth telluride - traditional thermoelectric material. The trade names of the modules are: TEC1-12715, TEC1-12710 and TEC1-12708. Basic technical data are given below in Table 2. Measurements were collected by a measurement electronic card on a PC unit. Series of measurements were conducted on the three modules mentioned above. The basic recorded parameters were: hot water inlet/outlet temperature in hot heat exchanger, inlet/outlet temperature in cold heat exchanger, the electric current and voltage occurred in the electric circuit (Fig. 3).

Module	TEC1-12715	TEC1-12710	TEC1-12708
T_{hot} [°C]	50	50	50
ΔT_{max} [K]	79	79	75
U_{max} [V]	17.2	17.2	17.5
I_{max} [A]	15	10.1	8.4
Q_c [W]	164.2	110.5	79
R []	0.79 ÷ 0.98	1.27 ÷ 1.49	1.8

Table 2: Technical data of thermoelectric modules

During the experimental work the temperature drops of water on both exchangers was obtained, the thermal power supplied to the thermoelectric module and

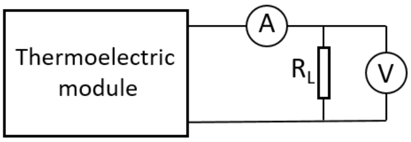

Figure 3: Schematic diagram of the measurement electric circuit

the electric power obtained on the receiver were measured too. Table 3 shows selected measurement data and computing values resulting from TEC1-12715 module examination. The measurements were used

T_{hot} [°C]	ΔT [K]	I [μA]	U [V]	P [mW]
62.06	69.07	333	1.55	0.52
62.25	69.35	334	1.56	0.52
62.44	69.57	342	1.6	0.55
62.69	69.88	339	1.58	0.54
63.38	70.5	340	1.59	0.54
63.5	70.69	340	1.59	0.54
63.69	70.95	342	1.6	0.55
63.88	71.17	343	1.6	0.55
64.12	71.44	345	1.61	0.56
64.31	71.69	348	1.63	0.57
64.56	71.94	356	1.67	0.6
65.37	72.75	360	1.69	0.61
66.12	73.5	363	1.7	0.62
66.81	74.22	366	1.72	0.63
67.5	74.91	370	1.73	0.64
68.19	75.56	373	1.75	0.65
68.81	76.22	376	1.77	0.67
69.5	76.94	380	1.78	0.68
70.12	77.56	374	1.75	0.66

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

to prepare the voltage characteristics of thermomodules depending on the temperature difference between the upper and lower heat sources (Fig. 4).

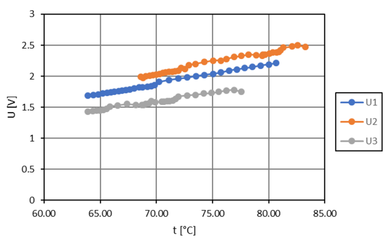

Figure 4: Voltage characteristics of Peltier modules as a function of the temperature difference (U1 - TEC1-12715, U2 - TEC1-12710, U3 - TEC1-12708)

The preliminary research results show that the level of voltage generated is similar to values obtained by other authors [15]. The problem is obtaining very small electric current values, resulting in minimal electric power generation. The reason for this is the application of load resistance that is too high. Hence the vital conclusion: getting current from thermoelectric modules should be done in a circuit with low resistance or the energy should be stored properly. If not, low efficiency of power generation is observed. Moreover, operation with small ΔT (from 60 to 80 K) near ambient temperature gives low thermal conversion efficiency. Therefore, modifications are required to both experimental setup and how related experiments are conducted.

5 Conclusions

This paper describes an application of Peltier thermomodules for the generation of electric current. Either waste heat or renewable energy sources are used to generate electric energy . Current and prospective materials were used. Basic mathematical relations were shown and the effectiveness of generating electric energy was analyzed. The experimental setup, method of taking measurements and interpreting them were were described. The results of the experimental work provide directions for future research i.e. using materials with a better ZT coefficient, increasing the temperature difference between the 'hot' and 'cold' side of thermoelement, and seeking new heat sources. These issues are at present firmly in the research and development phase.

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