An innovative method of generating current and thermoelectric equipment for its realization

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Abstract. The paper assesses an innovative thermoelectric device used to generate a current by the conversion of thermal energy into electrical energy. The device has been created and verified. Until now, the efficiency of conventional thermoelectric batteries is for technical practice not sufficiently appreciated, because it does not exceed 3 %. A necessary condition needed for the implementation of the Seebeck thermoelectric effect is a sufficient and stable source of heat that provides an optimum temperature difference, but there are two other sufficient conditions for a significant increase in efficiency of thermoelectric batteries. These are concerned with the development of new materials for thermoelectric batteries and with the development of new construction of thermoelectric batteries.

For nearly 200 years, four thermoelectric effects, which coexist in reality, have been known: Seebeck, Thomson, Peltier and Benedick. By means of technical adjustments of the device, one of the thermoelectric phenomena may be preferred over the others. In the present case of thermoelectric current generation, it is primarily related to the application of Seebeck effect, and secondarily with the closely related but hardly measurable Thomson effect. The Seebeck thermoelectric voltage occurs in a closed electrical circuit composed of two conductors, which are made up of two different materials and whose ends have a perfect conductive contact ensured by soldering. When a temperature difference between these two connections has been established, the two voltages working against each other arise in the circuit and give rise to an electromotive voltage. As a result of this thermo-voltage it is created the thermoelectric current, which generates Joule heat. However, the conductors are not heated uniformly along their entire length, but they have different temperatures at different locations, therefore the Thomson effect is applied as well. As a consequence of this phenomenon, the thermoelectric voltage occurs also in a single homogeneous conductor and on the assumption that the conductor is heated to different temperatures in different locations.

Thermoelectric couples [1, 2, 3, 4] are connected in series and in a cascade connection in order to increase the thermoelectric voltage, forming a thermoelectric battery (Figure 1).
Figure 1. Classic cascade thermoelectric battery scheme
1 - connecting bridge, 2 - column with P-type conductivity, 3 - column with N-type conductivity, 4 - insulating layer, 5 - DC voltage reading due to heating of the bottom part of the thermoelectric battery

In terms of technical applications, however, the generated thermoelectric voltage is relatively very small (when using conventional thermoelectric materials, it is necessary to actuate a temperature difference as high as 100 °C to create a thermal voltage in the amount of millivolts), while, on the contrary, thermoelectric current is relatively high and the internal resistance, compared to the external load resistance, is relatively very small.

Because there are relatively little changes in the open circuit voltage of the load, thermoelectric battery can be considered as a source of current, precisely, a source of hard voltage. However, this kind of energy source is not very usable either in weak current or in heavy current electrical engineering.

Its efficiency tends to be very low, i.e. lower than 3 %. The development of advanced alloys and semiconductor materials has achieved up to 100 times higher values of thermoelectric voltage than when metal materials were used [5, 6, 7, 8]. But even the use of advanced thermoelectric materials does not lead to the anticipated results in technical practice.

Semiconductor materials [9, 10, 11] (in this paper we deal with ternary alloys) have good thermoelectric properties (relatively low specific electric resistance and low thermal conductivity), but their efficiency is undermined by an important construction element, which is a copper bridge connecting the semiconductor pillars.

Although copper has a relatively high specific electric conductivity and allows good soldering, however, at the same time, it also diffuses into the semiconductor material and impairs its thermoelectric properties. In the point of contact between the bridge and the semi-conductor, there is an undesirable contact resistance, which may adversely affect the achievable thermocouple efficiency, as well as the maximum achievable temperature difference between the two contact points.

The development of new thermoelectric materials will be useless for applications in technical practice, unless a technological process of production capable of ensuring low contact resistance of the thermocouple is discovered. Thermal amortization represents another factor significantly influencing the efficiency of thermoelectric battery in technical practice, as the semi-conductor materials are more efficient than the metal ones, but their heat load is limited. Finding relatively substantial waste heats as suitable sources of conversion would be useless as well if the thermoelectric battery „disintegrates“ due to thermal amortization. Soldering has a significant technological impact on the thermoelectric battery elements, which shows itself only during long-term and more demanding operation in technical practice or in a laboratory.

Thermoelectric battery composed of thermoelectric coils (Figure 2) is a proposed innovative design solution that requires the incorporation of a problematic construction element - the copper bridge connecting the pillars.
Figure 2. Equipment for generating thermoelectric current using temperature difference
1 - coil with special metal-coated threads from another metal material, 2 - cold water tube, 3 - metal heating element from a resistance conductor, 4 - power supply of a metal heating element from a resistance conductor (3), 5 - electrical circuit with a source of direct current, 6 - sensitive ampere-meter

The proposed solution to generate thermoelectric current (Figure 2) consists of a special metal-coated coil forming threads (1), with an implemented inlet cold water tube (2) and also a rodlike shaped heating element (3) powered by an electric power source, (4), while the coil output conductors are powered by a DC source (5) and the electric current is controlled by measurements using a sensitive ampere-meter (6).

Seebeck thermoelectric voltage is practically difficult to measure, which is why it is more suitable to theoretically evaluate and measure the thermoelectric current.

Thermoelectric voltage generating thermoelectric current can be determined as a maximum Seebeck thermoelectric voltage $U_{S\text{max}}$ at the so called neutral temperature $T_n$, by empirically verified relation [12, 13, 14, 15]

$$ U_S = (a_1 - a_2)(T_1 - T_2) + \frac{1}{2}(b_1 - b_2)(T_1 - T_2)^2 $$

The peak $V$ of the parabolic course of the thermoelectric voltage $V = [U_{S\text{max}}, T_n]$ is given as a local extreme of function $U_S = U_S(\Delta T)$, while the thermoelectric material coefficients can be considered approximately constant, and temperature $T_2$ of the colder location can be considered constant as well.

The maximum value of Seebeck voltage and the neutral temperature can be derived as follows [4]:

$$ U_{S\text{max}} = \frac{(a_1 - a_2)^2}{2(b_1 - b_2)}; \quad T_n = -\frac{a_1 - a_2}{b_1 - b_2} + T_2. $$

It doesn’t make sense to further increase the temperature of the heating point above the neutral temperature, because the value of the maximum Seebeck thermoelectric voltage would decrease. The optimal thermoelectric current value $I$ can be evaluated in the following way, using Ohm's law for closed circuit.

The numerator is the Seebeck thermoelectric voltage, the denominator is the sum of the partial resistances, i.e. the resistance of $R$ load (appliance) and the resistances of both conductors $R_1$, $R_2$, which are heated in the joints. The conductor resistance values are evaluated according to their geometrical dimensions, their material and their electrical resistance temperature change.
The coil threads should ideally have the highest possible radius, because, in reality, the distance between the cold and heated locations should be significant in order to increase the thermoelectric voltage only in the range of millivolts.

The thermoelectric coil was implemented within the scope of the functional model only for the purpose of verification of its functionality, without any optimization of its parameters.

Material. The coil was made from the material, which does not show good thermoelectric properties. An air core coil was wound from a commonly available metal conductor (i.e. conductor made of electrochemical copper, with Seebeck coefficient of $a_{Cu} = 3.2 \, \mu V K^{-1}$in reference to platinum). This conductor was evenly coated with a thin metal layer of another material (tin, Seebeck coefficient of $a_{Sn} = 4.2 \, \mu V K^{-1}$ in reference to platinum). Contact voltage is due to low value of the resulting Seebeck coefficient extremely low. The electrical and thermal conductivity of copper is excellent and therefore, the particles of copper diffuse within a conductive bridge into a semiconductor material and degrade its excellent thermoelectric properties. It can be estimated that when choosing this type of material, tens of degrees Celsius from a possible source of waste heat and hundreds of optimized coil threads would increase the thermoelectric voltage only in the range of millivolts.
prevent the temperatures affecting each other. In addition to that, the thermal conductivity of copper is excellent and it impairs the temperature difference. The thermal coil had 20 threads, the threads had a radius of 4.5 cm, and they were wound using a conductor of radius 1 mm. The thickness of the coated layer has not been measured.

**Temperature difference.** The coil was simultaneously heated and cooled in opposite locations (Figure 2), using a metal tube with cold water and a metal rod shaped heating element. The metal tube was inserted into the coil cavity just below the coil thread inner surface and it was connected to the cold water inlet from a water conduit with constant temperature of 12 °C. Rod shaped heating element was also inserted into the coil cavity just below the coil thread inner surface opposite the cooling tube, while powered by a 12 V DC power source and it generated heat with a contact temperature of 300 °C. The temperature difference between the heating and cooling locations was measured using thermoelectric thermometers, by means of contact measuring from the temperatures scanned on the surface of the coil threads. As a result of the temperature difference and the contact voltage, thermoelectric voltage measurable by a micro-voltmeter was induced and, thermal voltage measurable by a sensitive milliampere-meter was a result of that. All the thermal phenomena are characterized by considerable inertia, which is why all the partial measurements (currents and temperatures) were performed in equidistant half-minute intervals.

**Efficiency.** A comparative device with the same geometric dimensions and from the same material, but without implementation of proposed innovations, has been created in order to measure the thermal current value depending on the temperature difference. Effectiveness of innovation was evaluated experimentally as a ratio of the measured currents generated at the same temperature difference by using both devices. The innovated thermoelectric battery has been evaluated as a functional device, but the mean efficiency was insufficient (0.65 %) at a maximum temperature difference of 50 °C. Low equipment efficiency was a result of the selection of readily available, but very inefficient thermoelectric materials (electrochemical copper and tin).

The paper assesses an innovative thermoelectric device generating thermoelectric current, which was realized as a functional model. Because there was no material with suitable thermoelectric properties available for production of the thermoelectric battery, the thermoelectric battery has been verified as functional, but with poor efficiency. A classic cascade construction of the thermoelectric couple was replaced by an innovative thermo-coil construction, the threads of which (made of electrochemical copper) were coated with a metal of another material (tin). The temperature difference required for the formation of thermoelectric voltage and thermoelectric current was simulated artificially in a laboratory, but in technical practice, comparable temperature differences may arise, for example, due to heating, preferably due to heating taking advantage of waste heat. The thermoelectric device will serve for two purposes: disposal of unwanted waste heat and clean conversion into electrical energy.

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