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THERMOELECTRIC ENERGY CONVERSION: STATE AND TRENDS

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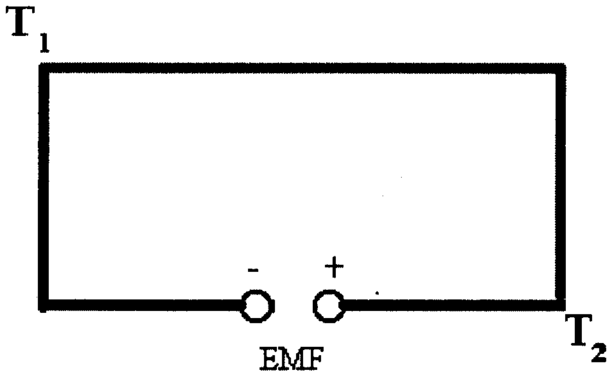
1. Introduction

Thermoelectric energy conversion has a great number of applications. This method of energy conversion has two main advantages: it is absolutely clean environmentally and it is a direct method of conversion.

Three directions of thermoelectric conversion are discussed in the paper: electric energy generation, cooling and measurements. The resent achievements in development of new extremely effective thermoelectric materials also are disputed.

2. Thermoelectric effects as a way of direct energy conversion

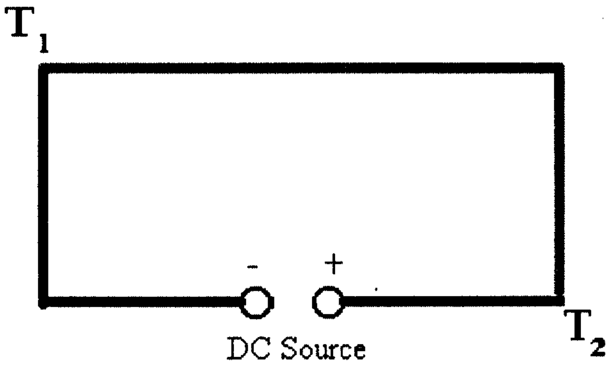
In 1823 Seebeck invented a new effect. The effect is based on the electric current in aclosed circuit formed by heterogeneous conducting materials, when the contact points of materials have different temperatures (Fig.1).



Temperature difference
⇒ EMF

Fig.1. Seebeck effect

About 12 years later, a complementary effect was invented by Peltier. He observed temperature changes in the vicinity of the junction between dissimilar conductors when a current paced (Fig. 2).



Electric current ⇒
temperature difference

Fig. 2. Peltier effect

Both Seebeck and Peltier effects are the two main thermoelectric effects, that can be used for many different applications.

Really, the Seebeck effect means that we are able to convert a heat into electric energy. Therefore, the Seebeck effect can be utilised for generating the electric energy and for measuring heat parameters. Moreover, in that case, we have a direct method on converting a heat into electricity without having any moving aggregates.

In turn, the Peltier effect can be adapted for decreasing the temperature, hence for cooling or refrigerating systems.

3. Requirements to **thermoelectric** materials

Let us look for requirements for the selection of thermoelectric materials prior to discuss applications of the thermoelectric effects.

It can be shown that property of thermoelectric materials are characterized by so called thermoelectric figure of merit Z that is determined by [1]

$$Z = \frac{\sigma S^2}{\kappa}, \tag{1}$$

where σ is the electrical conductivity, κ the thermal conductivity and S the thermoelectric power of a thermoelectric material.

The figure of merit of semiconductors is on one or two orders higher than that of metals. Therefore, semiconductors are the modern thermoelectric materials. It is necessary to underline that the figure of merit of semiconductors depends on temperature. Then, the different kinds of semiconductor materials should be selected for different operating temperatures.

The thermoelectric materials can be disassociated in dependence of an operating temperature into three classes [1,2]:

1. Low temperature materials are operated at $T < 300^0 C$. Such materials based on bismuth telluride as Bi_2Te_3, Bi_2Te_3-Bi_2Se_3, Bi, Bi-Sb.
2. Medium temperature materials are operated at the range $300^0 C < T < 600^0 C$. The PbTe, GeTe and $AgSbTe_3$ are such materials.
3. High temperature materials are operated at $T > 600^0 C$. The solid solutions on the base of Ge-Si and metals can be qualified as high temperature materials.

4. Advantages of **thermoelectric** converters

A modern thermoelectric module (a unit thermoelectric converter) consists of a number of alternate ingot-shaped n- and p-type semiconductor branches. They are connected electrically in series with metallic connection strips, sandwiched between two electrically insulating but thermally conducting ceramic plates to form a module (Fig.3). Provided temperature difference is maintained across the module, electrical power will be delivered to an external load and the device operates as a generator or a measuring device [1]. Conversely, when an electric current is passed through the module, heat is absorbed at one face of the module, rejected at the other face, and the device operates as a refrigerator [1].

The thermoelectric generating and cooling modules as energy converters are a solid state device. Therefor they have the following principally advantages that make them the only effective solution for certain applications:

1. They are absolutely clean environmentally.
2. They are very flexible and simple in operation.
3. They are highly reliable and theirs lifetime is more than 20 years.
4. They have no moving parts, and thus they do not produce any noise or vibration and produced minimum electrical noise.
5. The thermoelectric modules have a small size and light weight.

6. Their parameters do not depend from a space orientation,
7. They can work under large mechanical overloads.
8. The thermoelectric converters do not need any technical service and can operate in autonomous condition.

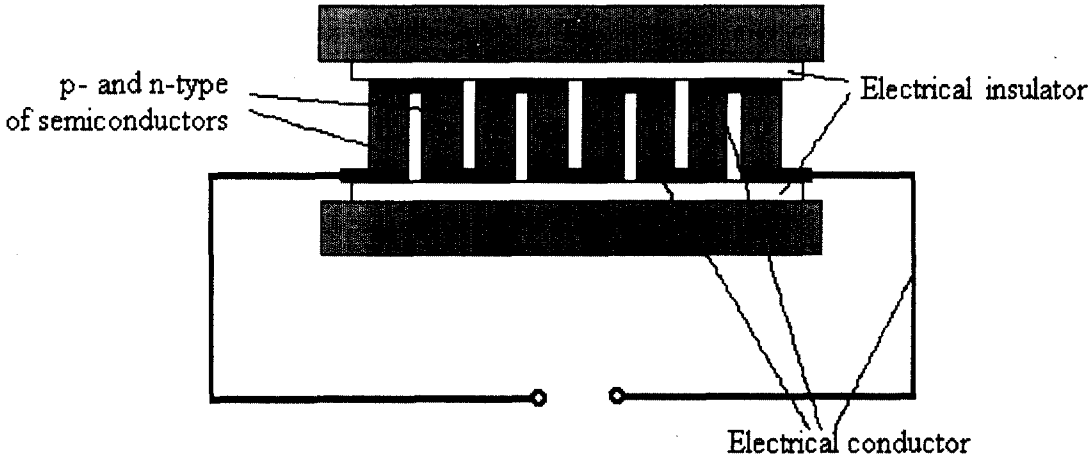


Fig. 3. Thermoelectric Module

5. Thermoelectric generators

The main parameter of an electric generator is the efficiency $\eta = \frac{P}{Q_h}$, where P is the electric power output and Q_h the heat input.

The maximum efficiency of a thermoelectric generator can be written as [2]

$$\eta_{\max} = \eta_0 \frac{M-1}{M+\frac{T_c}{T_h}}, \qquad \eta_0 = \frac{T_h - T_c}{T_h} \tag{2}$$

where T_c is a temperature of a cooler and T_h a temperature of a heater, η_0 the efficiency of the ideal thermodynamic Carnot machine and $M = \sqrt{1+T_M Z}$, $T_M = \frac{T_c + T_h}{2}$ the average temperature.

Under the conditions of maximum electric power output the efficiency of thermoelectric generator is [2]

$$\eta_P = \eta_0 \frac{1}{\frac{4}{ZT_h} + 2 - \frac{\eta_0}{2}}. \tag{3}$$

Usually the difference between the η_0 and η_P do not exceed 4%.

Thermoelectric generators can be disassociated into following several classes according to the source of heat energy: generators using chemical fuel, that include gas, liquid fuel (kerosene, benzine) and solid fuel (coal, wood); solar generators; radioisotope generators; generators on nuclear fuel.

The preceding advantage of the thermoelectric generators lead to a different kinds of applications. Let us enumerate the main of advantage[1,2]:

1. *Terrestrial applications* include the power supply for weather stations; navigation aids (the most immediate use is for light); subsea operations, especially for subsea petroleum

wellheads; communications systems such as radio, television, telephone and microwave stations; cathodic protection of corrosion at petroleum and gas transport industries.

2. In *space application,* the thermoelectric generators is the only possible solution for far space systems. The space nuclear power sources have provide to be reliable, long-lived sources of electrical power that have enabled the conduct of a number of USA and Russia space missions.
3. On the other hand, the very important application of thermoelectric generators is *the use of a low potential heat.* The sources of such a heat are a waste heat of industries, geothermal energy, ocean thermal energy and solar ponds. Utilisation of such sources of the energy is absolutely clean environmentally and protects heat pollutions.

6. **Thermoelectric** measuring devices

The energetic efficiency of the thermoelectric measuring devices also can be calculated by equations (2), (3) as that of the thermoelectric generators.

The main thermoelectric measuring devices are the following:

1. *Thermoelectric thermometers* are used for precision temperature measurement. One junction of a differential thermocouple has a fixed known temperature, and the second junction measures an unknown temperature. Different metals usually are used as a material for thermocouples.
2. *Converters for measurement the electric values* utilised the fact that the Seebeck thermoelectric power does not depend on the direction of electric current in an original electric circuit. Therefor a thermoelectric module can measure the effective values of electric parameters.
3. *Microcalorimeters* are thermoelectric devices for measuring a low level of heat, that produced in a closed capacity.
4. In *infrared thermal detectors* radiation is absorbed at the sensitive region of the detector, which heats up. A temperature difference is established across the thermocouples and an electrical signal generated by the Seebeck effect [1].
5. *Heat flow meters* used for measuring of a conductive and convection heat flow densities.

6. **Thermoelectric** coolers

The thermoelectric method of refrigeration does not need CFCs, and therefore it has principal advantage that it does not harm the ozone layer, and is an environment friendly method of cooling. Thermoelectric cooler performs the same cooling function as CFC-based compression-type refrigerator. A thermal energy is extracted from a region, thereby reducing its temperature, and then is rejected to a "heat sink" region of higher temperature. The vapor-cycle device requires a working fluid as a refrigerant, while the thermoelectric elements use the electron gas as a refrigerant.

It is well known that the main energetic characteristic of a refrigerating system is the coefficient of performance (COP). The COP is determined as $\varepsilon = \frac{Q_c}{W}$, where Q_c is a cooling power and W the corresponding electrical power.

The maximum COP of a thermoelectric cooler can be written as [2]

$$\varepsilon_{\max} = \varepsilon_0 \cdot \frac{\sqrt{1+ZT_M} - \frac{T_h}{T_c}}{\sqrt{1+ZT_M} + 1}, \qquad \varepsilon_0 = \frac{T_c}{T_h - T_c} \tag{4}$$

where T_c is a temperature of a cold side of thermoelement and T_h a temperature of a heat side, the complex ε_0 is the COP of the ideal thermodynamic Carnot cooling machine.

Under the condition of maximum cooling power Q_c the COP becomes [2]

$$\varepsilon_q = \frac{1}{2T_h}\left(T_c - \frac{2(T_h - T_c)}{ZT_c} \right). \tag{5}$$

It is necessary to underline that unlike compressor-type refrigerators, a thermoelectric cooler can maintain their COP down to very low values of Q_c, of the order of milliwatts [1]. It is very simple for a thermoelectric cooler to change an operating mode from the behavior of $\varepsilon_{\max}$ to the behavior of $Q_{c\max}$, or to operate in some medium condition.

Let us discuss the main applications of thermoelectric cooling:

1. Applications for *consumer purposes* include different kinds of portable picnic boxes, home refrigerators; coolers for drinks, water coolers-purifiers, medicine coolers, etc.
2. Thermoelectric coolers for *transport* can embody automobile air-conditioners, automobile mini-refrigerator boxes, automobile seat coolers, aircraft drinking water coolers, the railway-carriage air-conditioner.
3. In *industry* we can meet the thermoelectric coolers that make the temperature control of different systems as PC computer microprocessors, electronic systems, fiber optics and laser diode.
4. Medical applications include instrument for blood analyzers, hypothermia blankets, portable and stationary pharmaceutical refrigerators, tissue preparation and storage, cryosurgical destroyer, microscope stage cooler, cold plate for dental cement, mist tent, hospital personal refrigerators, etc.
5. In shops and restaurants they are used for cooling bars, cooling windows, cream and butter dispensers, coolers for milk, individual portion dispensers, etc.
6. Very various are applications for laboratory equipment, that include coolers for infrared detectors, photomultiplier tube housing coolers, charge coupled device coolers, charge induced device coolers, integrated circuit coolers, vidicon tube coolers, laboratory cold plates, stir coolers, cold chambers, immersion coolers, ice point reference baths, electrophoresis cell coolers, osmometers, dewpoint hygrometers, air pollution control analyzers, oil pour point apparatus, constant temperature baths, thermostat calibrating baths, heat density measuring and so on.

7. Trends of thermoelectric energy conversion

Three main factors that lead for great progress in thermoelectric energy conversion may be selected.

At the first, research and develop results in the last 4-5 years ascertain possibilities of strong increase of the thermoelectric figure of merit in 2.2-2.7 times by using some principally new thermoelectric materials [3-5]. Such a increasing in the thermoelectric figure of merit Z leads to strong increasing of efficiency of thermoelectric generators and COP of thermoelectric coolers.

The second factor is the advantage of the thermoelectric conversion that leads to an absolutely clean environment.

Finally, at the situation of lack of fossil fuel the thermoelectric generators that use wasted heat give the possibility of energy saving and decrease of heat pollution in environment.

It should be noted that these three factors will drive for significant improvement of the thermoelectric converter's performance.

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