THERMOELECTRIC HANDBOOK

THERMOELECTRIC EFFECTS

Two thermoelectric effects have gained the greatest practical application: the Peltier effect and the Seebeck effect.

The Seebeck effect (discovered in 1822).

In an electric circuit consisting of two different conductors, the contacts of which are at different temperatures Th and Tc, an electromotive force arises, the so-called thermoEMF.

$U=(\alpha 1-\alpha 2)\cdot(Th-Tc)$; where $\alpha 1$, $\alpha 2$ are thermoelectric coefficients, or as they are called, the Seebeck coefficients of conductor materials.

The highest thermoEMF value is observed in a circuit consisting of semiconductor materials of n- and p-type conductivity.

The Seebeck effect has found application in thermoelectric generators and detectors.

The Peltier effect (discovered in 1834).

When electric current I passes through the contact of two different conductors, heat is released or absorbed at the point of contact, depending on the direction of the current.

Cooling (heating) power $Q=P\cdot I$, where $P=(\alpha 1-\alpha 2)\cdot T$ is the Peltier coefficient.

The largest value of the Peltier coefficient is observed in an electric circuit consisting of semiconductor materials of n- and p-type conductivity.

The Peltier effect has found application in thermoelectric coolers and heaters.

THERMOELECTRIC COOLERS

What is a thermoelectric cooler?

A thermoelectric cooler is a solid-state heat pump, the operation of which is based on the Peltier effect. Such a cooler has no moving parts, so it is a very reliable device.

A thermoelectric cooler consists of one or more thermoelectric modules and a heat sink.

A standard thermoelectric module consists of semiconductor thermocouples connected in series electrically and in parallel thermally, being located between two ceramic plates and forming a non-dismountable structure. The thermoelectric module is the main component of thermoelectric instrumentation.

Modules of different designs and with different characteristics are produced industrially to create thermoelectric devices.

THE OPERATING PRINCIPLE OF A THERMOELECTRIC COOLER

Figure 1 illustrates the work of a thermoelectric module in cooling mode.

When the positive terminal of a DC source is connected to an n-type element in a thermocouple, the electrons move from a low energy level in the p-type element to a high energy level in the n-type element. As a result, the Peltier heat is absorbed at the contact and this contact (junction) cools. This heat is proportional to the current and the number of thermocouples. Heat is then transferred across the thermocouple elements to the opposite junction and released at the contact as the electrons return to a low energy level in the p-type element. This junction heats up. Changing the direction of the current changes the direction of the heat flow. Adjusting the direction and value of the current using a temperature controller allows the thermoelectric module to cool, heat or stabilize the temperature.

In addition to the absorption and release of the Peltier heat at the thermocouple junctions, the Joule heat is released in the bulk of the thermocouple legs. Approximately half of the Joule heat goes to the cold junction, and half to the hot junction. Since the Peltier heat absorbed at the cold junction, is proportional to the current, and the incoming Joule heat is proportional to the square of the current, there is a certain value of current above which cooling will be reduced. The value of current that realizes the greatest cooling ΔTmax, is designated Imax

Practically, cooling cannot be realized without effective removal of heat from the hot surface. Heat removal (air or liquid heat exchangers) is used to remove heat from the hot surface of the module to the environment. Heat dissipation is characterized by thermal resistance Rth. The value of Rth is equal to the excess of the heat removal temperature over the ambient temperature when dissipating a heat flow of 1W.

SINGLE-STAGE COOLING MODULE

A single-stage thermoelectric cooling module consists of a number of thermocouples connected in series electrically and in parallel thermally. Each thermocouple consists of series-connected semiconductor elements of p- and n-type conductivity. Bi2Te3-based semiconductor materials, which have the highest efficiency, are usually used as element materials. The maximum temperature difference of a single-stage standard module at a hot surface temperature of 25°C is 68-74°C. An increase in the hot side temperature leads to an increase in Tmax.

A standard module may contain one or more thermocouples located between two ceramic plates. These plates form the hot and cold surface of the module and provide structural integrity. Due to the fact that the plates are a good electrical insulator and heat conductor, they act as a cooling and heat removing surface.

The contact surfaces of the ceramic plates must be parallel to each other with high precision and have low roughness. This significantly reduces the contact thermal resistance of the mounted module. The contact surfaces of the plates may contain a multi-layer metal coating, which is necessary for the assembly of the module by the soldering method.

The electric leads of the module are located on the hot side and have such a length that it is possible to realize connection by soldering without damaging the module. The positive lead of the wire is red.

The maximum operating temperature of the module is limited and is usually 120-150°C. High temperature modules can operate at a maximum temperature of 200°C.

In order to increase the service life of the module, special highly reliable contacts of thermocouple elements are formed. Such modules can withstand a large number of deep thermal cycles and have a long service life without reducing Tmax. The cost of such a module is higher than that of a regular one, and it can be custom made.

The module can be made sealed, the thermocouples in it are protected by a sealant. This protects thermocouples from moisture and reduces heat loss.

According to the geometric configuration, standard modules can be rectangular or round. Modules with a round hole can be used in optics.

MULTI-STAGE COOLING MODULE

A multi-stage thermoelectric cooling module is formed by several single-stage modules installed vertically one above the other thermally in parallel. In such a module, the upper stages are cooled by the lower ones. The modules of the stages are selected so that the lower module absorbs all the heat released by the upper stage.

Multi-stage modules offer two main advantages:

1. For a given temperature difference, a multi-stage module has greater efficiency than a single-stage module. Efficiency increases significantly when moving from a single-stage to a two-stage module. The use of a three-stage module gives a much smaller effect and practically exhausts the possibility of further increasing efficiency.
2. With a multi-stage module, a larger temperature difference Tmax is achieved, since the lower stage reduces the temperature level of the upper stage.

ΔTmax is determined by the number of stages and the efficiency of the thermoelectric materials used. If a deeper cooling is required, the number of stages can be 5-7. On a seven-stage module at a hot side temperature of 27°C, ΔTmax=150°C was achieved.

The cooling capacity value of a multi-stage module ranges from a few fractions of Watt to 50W. Usually, several modules are connected to increase the cooling capacity.

According to their functional purpose, multi-stage modules can be standard, high-temperature and with increased service life.

CHARACTERISTICS OF A THERMOELECTRIC COOLER

Cold side temperature, Tc, °C.
Hot side temperature, Th, °C.
Temperature difference on a module, ΔT=Th-Tc, °C.
The maximum and operating characteristics of the module are determined for a given value of Th.

Maximum characteristics

Maximum current, Imax, A; current that realizes maximum cooling.
Maximum voltage, Umax, V; electric voltage on the module at current Imax and no

thermal load on the cold side of the module ($Q_c=0$).
Maximum temperature difference, ΔT_{max}, °C; temperature difference on the module at current I_{max} and no thermal load on the cold side of the module ($Q_c=0$).
Maximum cooling capacity, Q_{max}, W; heat flow power on the cold side of the module at current I_{max} and no temperature difference across the module ($\Delta T=0$).

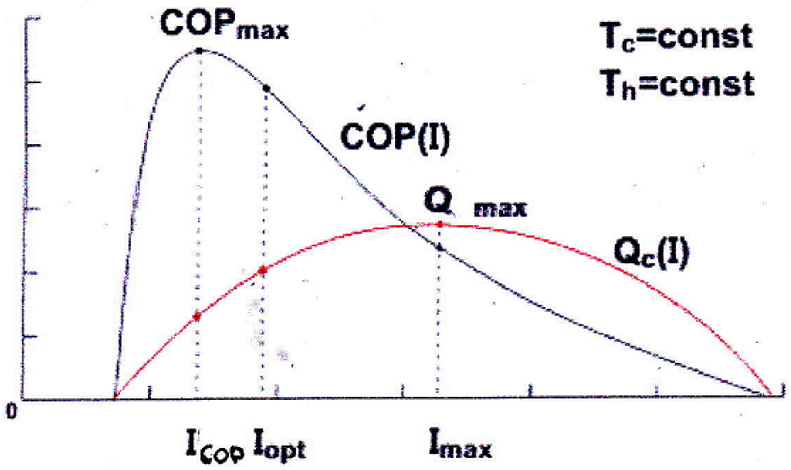
Operating characteristics
Operating current, I, A; current through the module that realizes the necessary cooling.
Operating voltage, U, V; voltage on the module at operating current.
Electric power, P, W; electric power of the module is determined by the formula $P=I \cdot U$.
Cooling capacity, Q_c, W; power of the heat flow on the cold side of the module, whereby the required temperature difference is realized in the operating current mode.
Thermal flow on the hot side, Q_h, W is determined by the formula $Q_h=Q_c+P$.
Coefficient of performance, COP; module efficiency which is determined by the formula $COP=Q_c/P$

Geometric dimensions of module.
A, B – dimensions of the cold surface of cooling module, mm;
C, E – dimensions of the hot surface of cooling module
(with electric leads), mm;
H – module thickness, mm.

OPERATING MODES OF COOLING MODULE

There are three main operating modes of thermoelectric cooling module:
maximum temperature difference mode - ΔT_{max};
maximum cooling capacity mode - Q_{max};
maximum efficiency mode (maximum coefficient of performance) - COP_{max}.

Figure 2 schematically shows the relationship between the operating modes of the cooling module.



The temperature difference that occurs in the module is determined not only by the processes inside the thermocouple, but also by the magnitude of the thermal load on the cold surface of the module. The less heat flow from the environment onto a cold surface, the more its temperature can be reduced.

The maximum temperature difference Tmax is achieved under the conditions of thermal insulation of the cold side Qc=0 at a current value Imax.

The maximum cooling capacity Qmax is achieved under the condition ΔT=0, since in this case there is no heat flow between the hot and cold sides. The value of the maximum cooling capacity is determined by the value of the current Imax.

The Qmax mode is used in the case when it is necessary to achieve a low cost of the device and fast cooling, and the requirements for economy are not high.

The maximum value of the coefficient of performance COPmax is achieved at current Icop<Imax. The cooling capacity Qc in COPmax mode is noticeably lower. This difference increases with increasing temperature difference. In COPmax mode, a larger number of thermocouples (modules) are required to realize the set Qc value than in Qmax mode. COPmax mode has low power consumption, but high device cost. The advantage of this mode is that currently known thermoelectric materials do not provide such a high COP value that it can be reduced to reduce the cost of the device.

Of practical interest is the intermediate optimal mode COP-10%. Reducing the current from Icop to Iopt reduces the coefficient of performance by no more than 10%. At the same time, the cooling capacity is noticeably higher compared to the COPmax mode, which means the cost of the device is lower.

Formulae describing the device: thermoelectric cooler.

Maximum temperature difference, ΔTmax

$$\Delta T_{\max} = \frac{Z_d T_c^2}{2}$$

Maximum current, Imax

$$I_{max} = \frac{\alpha T_c}{R}$$

Voltage, U

$$U = IR + \alpha(T_h - T_c)$$

$$U_{max} = I_{max}R + \alpha\Delta T_{max}$$

Cooling capacity, Qc

$$Q_c = \alpha T_c I - 0.5I^2R - L(T_h - T_c)$$

$$Q_{max} = \alpha T_c I_{max} - 0.5I_{max}^2 R$$

Coefficient of performance, COP

$$\text{COP} = \frac{Q_c}{UI}$$

$$\text{COP}_{max} = \frac{MT_c - T_h}{(T_h - T_c)(M+1)}$$

Electrical resistance of the device, R

$$R = (r_p + r_n + 4\frac{r_k}{l})\frac{N}{G}$$

Thermal conductivity of the device, L

$$L = (k_p + k_n)GN$$

The Seebeck voltage of the device, α

$$\alpha = (\alpha_p - \alpha_n)N$$

Thermoelectric figure of merit of the device, Zd

$$Z_d = \frac{\alpha^2}{RL}$$

THERMOELECTRIC GENERATOR (TEG)

What is a thermoelectric generator?

A thermoelectric generator is a solid-state thermal into electrical energy converter, the operation of which is based on the Seebeck effect. Such a generator has no moving parts, so it is a very reliable device.

The design of a thermoelectric generator includes a heat source (heat flow collector), one or more thermoelectric modules and a heat sink. A standard thermoelectric module consists of a battery of semiconductor thermocouples, which are connected in series electrically and in parallel thermally, located between two ceramic plates and form a non-separable structure. The thermoelectric module is the main component of thermoelectric instrumentation.

OPERATING PRINCIPLE OF A THERMOELECTRIC GENERATOR

The thermoelectric generator uses the thermoelectric effect discovered by Seebeck. The operating principle is based on the physical phenomenon of the occurrence of an electric potential difference in an electric circuit formed by two different conductors if one contact is maintained at a higher temperature than the other
Figure 3 illustrates the work of a thermoelectric generator.

The reason for the Seebeck effect is the temperature dependence of the energy of charge carriers. A higher temperature leads to an increase in the energy of charge carriers and leads to their diffusion in the direction of decreasing temperature. Holes, or positive charge carriers, move in the p-type element towards the heat sink and provide a positive charge in the contact area on the cold side. Likewise, the flow of electrons in an n-type element provides a negative charge on the cold side in the n-type element. The redistribution of charge carriers in the elements leads to the appearance of an electric field that compensates for the diffusion flow of charge carriers. An electric current will flow in a closed circuit.
The electric power generated in a TEG is a consequence of conversion of the thermal energy of the charge carrier flow into electric energy. In practice, electricity generation cannot occur without effective heat removal. To remove heat from the hot surface of the module into the environment, heat removal (heat sink, air or liquid heat exchanger) is used.
Heat dissipation of TEG is characterized by thermal resistance Rtc. The value of Rtc is equal to the value of the excess of the heat removal temperature over the ambient temperature during the dissipation of the heat flow of 1W.

GENERATOR MODULE

Standard cooling modules are used in generation mode and find application for low-grade heat conversion. Typically, standard cooling modules use thermoelectric materials based on Bi_2Te_3, which have a maximum figure of merit at a temperature close to 25°C. The efficiency of a standard module at a hot surface temperature of 150°C and a cold surface temperature of 25°C is 4.1-5.1%. The maximum module efficiency for this temperature range is 5.5%. An increase in temperature difference leads to an increase in efficiency.

To increase the efficiency of the generator module, it is necessary to use thermoelectric materials in which the maximum figure of merit is within the operating temperature range. Therefore, the high temperature cooling module can be used as a TEG with greater efficiency.

A single-stage thermoelectric module consists of one row of thermocouples connected in series electrically and in parallel thermally. Each thermocouple consists of series connected p- and n-type semiconductor elements. Semiconductor materials based on Bi_2Te_3, which have the highest thermoelectric figure of merit, are usually used as element material.

A standard module may contain one or more thermocouples located between two ceramic plates. These plates form the hot and cold sides of the module and provide structural integrity. Due to the fact that the plates are a good electric insulator and heat conductor, they act as a cooling and heat dissipation surface.

The contact surfaces of the ceramic plates must be parallel to each other with high precision and have low roughness. This significantly reduces the contact thermal resistance of the mounted module. The contact surfaces of the plates may contain a multi-layer metal coating, which is necessary for the assembly of the module by the soldering method.

The electric leads of the module are located on the cold side of the module and are of such a length that allows connection by soldering without causing damage to the module. The positive lead of the wire is red.

The maximum operating temperature of the module is limited and is usually 150°C. High-temperature modules can allow operation at a maximum temperature of 200°C.

In order to increase the service life of the module, special highly reliable contacts are formed on thermocouple elements. Such modules withstand a large number of deep thermal cycles and have a long service life. The cost of such a module is higher than that of the usual one, and it can be custom made.

The module can be made sealed, the thermocouples in it are protected by a sealant. This protects them from moisture and reduces heat loss.

To create TEGs, rectangular and round modules are used.

CHARACTERISTICS OF A THERMOELECTRIC GENERATOR

Hot side temperature, Th, °C.
Cold side temperature, Tc, °C.
Temperature difference on the module, ΔT=Th-Tc, °C.
The maximum and operating characteristics of the module in the generation mode are determined for the given values of Th and Tc.

Maximum characteristics
Maximum electric power, Pg.max, W;
maximum electric power on load resistance.
Maximum power current, Ig.max, A;
electric current that realizes maximum power.
Maximum power voltage, Ug.max, V;
electric power that realizes maximum power.
Maximum power electric resistance, Rmax, Ohm;
load resistance at which maximum electric power is achieved.
Maximum efficiency, η.max;
maximum efficiency of thermal into electric energy conversion.
Maximum efficiency current, Ie, A;
electric current that realizes maximum efficiency.
Maximum efficiency voltage, Ue, V;
electric voltage that realizes maximum efficiency.
Maximum efficiency electric resistance, Re, Ohm;
load resistance at which maximum efficiency is achieved.
Electromotive force (EMF), E0, V;
electromotive force of the module in an open circuit (I=0).
Short circuit current, I0, A;
current in the electric circuit of the module at the value of load resistance equal to zero.

Operating characteristics

Electric current, Ig, A;
the necessary electric current on the load resistance.
Electric voltage, Ug, V;
the necessary electric voltage on the load resistance.
Electric power, Pg, W;
the necessary electric power on the load resistance; determined by the formula Pg=Ig-Ug.
Load electric resistance, Rload, Ohm;
load resistance at which the necessary electric power is achieved.

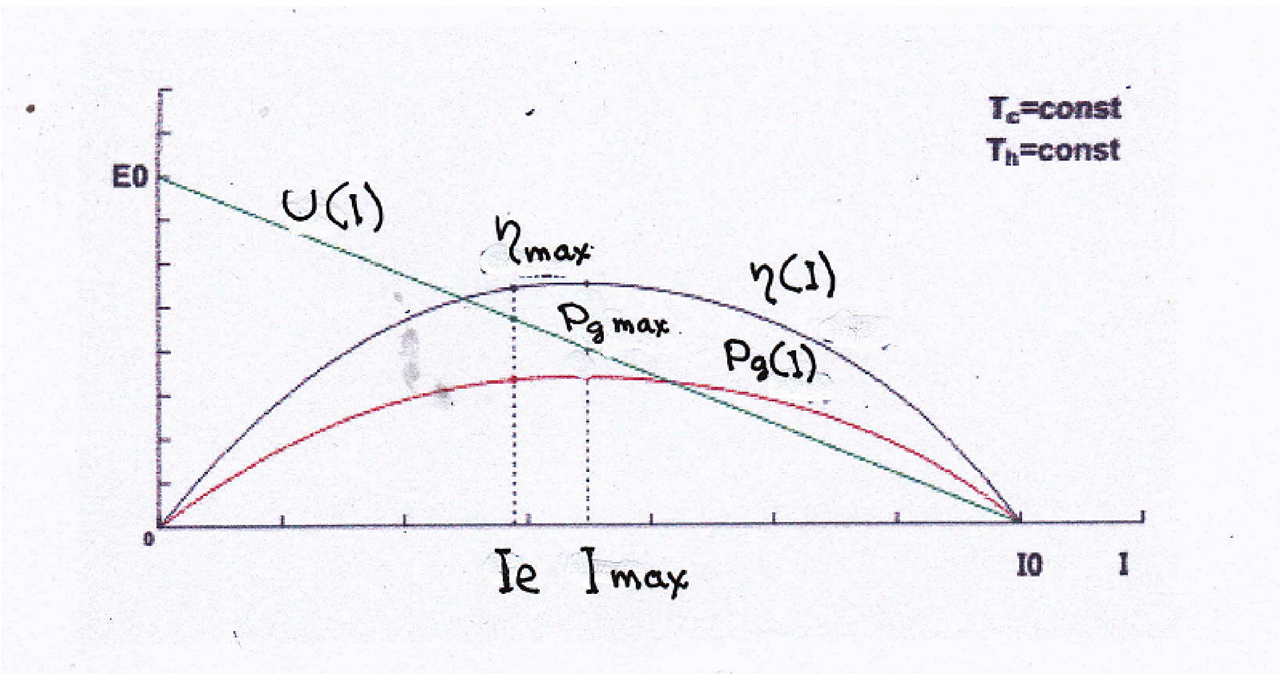
Power of the hot side thermal flow, Qgh, W;
power of thermal flow that comes to the hot surface of module from the heat source.
Power of the cold side thermal flow, Qgc, W;
power of thermal flow on the cold side of module that is dissipated by heat removal; determined by the formula Qc=Qgh-Pg
Efficiency, η;
efficiency of thermal into electric energy conversion; determined by the formula η=Pg / Qgh.

Geometric dimensions of the module.
A, B – dimensions of the hot surface of generator module, mm;
C, D – dimensions of the cold surface of generator module (with electric leads), mm;
E – module thickness, mm.

OPERATING MODES OF A THERMOELECTRIC GENERATOR

There are two operating modes of a thermoelectric generator: the maximum power mode and the maximum efficiency mode.
Electric power reaches a maximum when the load resistance Rload is equal to the generator resistance R in the operating temperature range (Rload=R).
The value of the maximum efficiency is achieved for the load resistance Rload≤1.35-R and depends on the figure of merit of the module Zd.

Figure 4 schematically shows the relationship between the operating modes of a thermoelectric generator.



Formulae describing the device: thermoelectric generator

Power

$$P_g = \frac{\alpha^2 (T_h - T_c)^2}{R} \frac{m}{(m+1)^2}$$

Load current

$$I_g = \frac{\alpha (T_h - T_c)}{(m+1)R}$$

Load voltage

$$U_g = \frac{\alpha (T_h - T_c)}{(m+1)}$$

Electromotive force of an open circuit

$$E_0 = \alpha (T_h - T_c)$$

Effectiveness (efficiency)

$$\eta = \frac{(T_h - T_c)}{T_h} \frac{\frac{m}{(m+1)}}{1 + \frac{m+1}{Z_d T_h} - 0.5 \frac{(T_h - T_c)}{T_h} \frac{1}{(m+1)}}$$

Load factor

$$m = \frac{R_{load}}{R}$$

Operating conditions
Maximum power Pg max=Pg (m=1)
Maximum efficiency η max=η (m=M)

Electric resistance of the device $R = (r_p + r_n + 4\frac{r_k}{l})\frac{N}{G}$

Thermal conductivity of the device, L

$$L = (k_p + k_n) GN$$

The Seebeck voltage of the device, α

$$\alpha = (\alpha_p - \alpha_n) N$$

Thermoelectric figure of merit of the device, Zd

$$Z_d = \frac{\alpha^2}{RL}$$

Designations

T_h – hot side temperature, K;

T_c – cold side temperature, K;
G=s/l; s - cross-sectional area of thermoelement;
l - length of thermoelement;
N – number of thermocouples;
$M=(1+0.5\bullet Zd\bullet(Th+Tc))^{0.5}$
αp, αn – average Seebeck coefficient value of p-, n-type thermoelectric material, μV/K.
rp, rn – average resistivity value of p-, n-type thermoelectric material, Ohm·cm.
kp, kn – average thermal conductivity value of p-, n-type thermoelectric material, W/(cm·K);
r_k – contact resistance, Ohm·cm^2.