Ministry of Education and Science of Ukraine
Ternopil Ivan Puluj National Technical University

Faculty of Applied Information Technology and Electrical Engineering
(full name of faculty)
Electrical Engineering Department
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QUALIFYING PAPER

for the degree of

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(degree name)

topic: **Thermoelectric converters of low-potential thermal energy**

Submitted by: fourth year student, group IEE-42
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« » 2022

ASSIGNMENT
FOR QUALIFYING PAPER

for the degree of Bachelor
(degree name)

specialty 141 Electrical Power Engineering, Electrical Engineering and Electromechanics
(code and name of the specialty)

student *Hasan Abdelrahman*
(surname, name, patronymic)

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Paper supervisor *Zakordonets Volodymyr, Ph.D., Assistant professor*
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Chapter	Advisor’s surname, initials and position	Signature, date	
		assignment was given by	assignment was received by
Labour occupational safety and security in emergency situations	*Ph.D., Assistant professor Okipnij I.B.*		
Compliance check	*Ph.D., Assistant professor Zakordonets Volodymyr*		

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	SECTION»		
3	Preparation of the «PROJECT DESIGNING SECTION»	21.02.22 – 30.03.22	
4	Preparation of the «LABOUR OCCUPATIONAL	01.04.22 – 20.04.22	
	SAFETY AND SECURITY IN EMERGENCY		
	SITUATIONS»		
5	Preparation of introduction, conclusions,	20.04.22 – 05.05.22	
	Content and summary.		
6	Preparation, execution and printing graphic material of	05.05.22 – 10.06.22	
	Bachelor's work		
7	Getting feedback and review of bachelor's work	11.06.22 – 24.06.22	
	and drafting a report for the bachelor's defense.		

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ABSTRACT

Qualifying work of the bachelor Hasan Abdelrahman contains: 65 pages, 32 figures, 4 tables, 48 references to primary sources.

The subject of researchthere are low-potential heat energy converters.

The purpose of the workis the creation and calculation of the parameters of a new device - a semiconductor thermoelectric-mechanical converter of thermal energy (TEMC), designed to convert low-power technology.

The object of studyis a semiconductor thermoelectromechanical low-potential heat energy converter.

Main results: The main parameters of the new device - the semiconductor thermal-electromechanical converter of thermal energy (TEMC), designed for low power. The principle of the interaction of the thermoelectric system, which is generated by short-circuited thermoelectric gene genes, is based on the principle of operation. In the motor mode, TEMC can operate as a mechanical drive in autonomous energy systems. Calculated mechanical power, electromagnetic moment, frequency of flood velocities and performed optimization. It is shown in principle that it is possible to work in thermophilic and thermally oxidizing conditions.

Keywords:low-potential thermal energy, thermal machine, Carnot cycle, thermoelectromechanical converter.

CONTENT

INTRODUCTION

Very quickly, during the twentieth century, mankind spent the most valuable raw material created on Earth for hundreds of millions of years - oil. Spent in an unreasonable way: about half of the oil goes to the production of fuel for vehicles. In addition, the extremely negative impact on the environment is due to the extraction of fossil fuels from our planet. Problems are associated with both the extraction of fuel and its transportation and, most importantly, its combustion, because the combustion of even "pure" fuels produces many harmful substances that enter the environment.

One of the main directions of economic development and scientific and technological progress in the XXI century is the task of finding promising technologies for energy conversion and mass production of new technology based on highly efficient thermodynamic cycles using renewable fuels and new fluids. This means the creation, production and widespread use of such highly efficient and environmentally friendly energy systems that would meet the needs of industry and

In all developed countries (primarily the EU and the US) the basis of innovative industrial development is the task of moving to a new technological level related to the environment, energy conservation, and reducing the share of traditional energy resources. In particular, by 2025, more than 20% of energy in the EU will be produced through the use of alternative and renewable fuels.

Due to the huge reserves of thermal resources in the bowels of the Earth and increasing demand for electricity, mechanical and thermal energy, the development and optimization of new devices that generate useful energy from natural and man-made heat is an urgent solution to energy shortages [1-9]. In addition, the conversion of large amounts of heat (about 70% of the world's energy) lost in various technological processes will help prevent possible global warming and climate change [8,10-12]. The global environmental crisis has also become a major issue. Emissions of fossil fuel combustion products into the atmosphere have reached alarming proportions.

The subject of researchthere are low-potential heat energy converters.

The purpose of the workis the creation and calculation of the parameters of a new device - a semiconductor thermoelectric-mechanical converter of thermal energy (TEMC), designed to convert low-power technology.

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The purpose of the workis to create, design and calculate the parameters of low-potential heat converter to mechanical.

The object of studyis a semiconductor thermoelectromechanical low-potential heat energy converter.

The subject of researchthere are low-potential heat engines with a solid working body.

Scientific novelty of the obtained results.

- A new device is constructed - a semiconductor thermoelectric-mechanical converter of thermal energy (TEMC) with a solid working body, designed for the conversion of low-potential thermal heat.
- The main parameters of TEMC in the motor mode are specified: mechanical power, electromagnetic moment, frequency of floods and efficiency.
- The optimization of TEMC parameters in the modes of maximum power and maximum efficiency is carried out.
- The calculation of the magnetic system of the device, which does not require additional energy costs to excite the magnetic flux.
- The calculation of the cooling system of the device, equipped with a system of heat pipes connected to a passive radiator of a large area.
- It is shown in principle that it is possible to run the converter in thermosetting and thermally oxidizing modes.

- **Practical value of research results**
- The design of a new device is proposed - a semiconductor thermoelectric-mechanical converter of thermal energy (TEMC), designed for the conversion of low-potential thermal energy.
- The design of a highly efficient cooling system of the device, equipped, is proposedsystem of heat pipes connected to a passive radiator of a large area.
- The design of the magnetic system of the device is proposed, which does not require additional energy costs to excite the magnetic flux.
- The results of a study aimed atincreasing the efficiency of conversion of low-potential thermal energy into mechanical energy.

1. ANALYTICAL SECTION

NON-TRADITIONAL AND RENEWABLE ENERGY SOURCES

1.1. Solar energy

Energy in the Sun is produced as a result of thermonuclear reactions to convert hydrogen to helium. Every second, more than 4 billion kilograms of matter is converted into energy emitted by the Sun into outer space in the form of electromagnetic waves. Less than one percent of solar energy falls to Earth. But this would be enough to meet all the energy needs of mankind.

Flat collectors. As a rule, flat collectors are made in the form of flat water collectors which are placed on roofs of houses or other surfaces.[1,2]. The amount of energy that can actually be used depends on the efficiency of the collector and the device that converts solar energy into useful energy. Since the intensity of solar radiation is relatively small, the size of the collectors to capture solar energy must be significant. For example, in sunny areas of the United States, the size of the collector, which can meet the energy needs of one person is about 40m2.

Fig. 1.1 Flat solar collector

In the simplest case, a flat collector is a dark metal sheet covered with one or two layers of glass that absorbs heat energy. Subsequently, the heat is transferred to the water. Such collectors can provide heating of the heat carrier to 65-90 ° C, and their efficiency makes about 20-80%.

When using liquid coolant, a number of parallel pipes with a diameter of 12-16 mm are used, which are in thermal contact with a metal sheet and are located at a distance of 50-150 millimeters from each other. The collector body is made of metal, wood or plastic. Externally, the housing is insulated with thermal insulators.

Solar water heaters. Currently, the world operates more than 5 million solar water heaters. They are often used in residential buildings, centralized hot water supply systems in residential and public areas, hospitals, sports and recreation complexes, etc. Industrial production of such heaters is established in many countries, including the United States, Australia, France, etc .. Energy It is advisable to use the sun in areas with more than 1,800 hours per year of solar radiation. Solar water heaters are quite popular due to the simplicity of construction, high reliability and quick payback [2]. It is obvious that the use of solar energy is becoming a symbol of the XXI century.

Collectors-concentratorsused when you want to reach high temperatures [2,3]. Installed in the right places, solar collectors-concentrators can focus solar radiation on the water tank (Fig. 1.2).

Fig. 1.2 Solar collectors-concentrators

The largest solar power plant is located in the Mojave Desert in California. It consists of a large number of parabolic mirrors, in the focus of which are tubes. Evaporating water circulates through the tubes. To generate electricity, superheated steam is fed to the turbogenerator. The main inconvenience is that electricity is generated only when the sun is shining, and is not generated on cloudy days and nights. Therefore, often, solar power plants use hybrid technologies - during the day they use solar energy, and at night turn on conventional water boilers in which natural gas is burned.

Solar generationis carried out by direct conversion of solar radiation into electricity using photovoltaic cells [4].

In 2020, the total capacity of all solar panels installed on Earth was more than 760 GW, which corresponds to approximately 2.7% of global electricity generation. [4].

Fig. 1.3 Solar power plant

1.2. Energy of sea waves

Wave energy on the surface of the seas and oceans, like any other energy, can also be used to operate power plants[5]. According to experts, the waves of the oceans can meet up to 20% of human energy needs.

Fig. 1.4 Wave power plant

According to the boldest estimates, sea waves generate about 2 TW of energy, which is twice the total amount of electricity production worldwide. The attractiveness of using sea waves is their high energy consumption. In particular, the specific power of water in its level significantly exceeds that of solar and wind energy. In the case of waves of ten meters high, the specific power is 2 MW per running meter. At the heart of the operation of marine power plants is the principle of action of waves on certain working bodies.

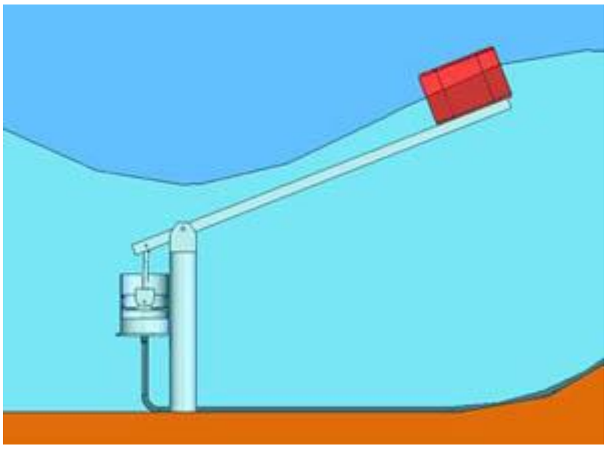


Fig. 1.5 The principle of using the energy of sea waves

The role of the latter may be, depending on the specific project, turbine blades, pumps, pendulums, etc .. The movement of sea waves is eventually converted into the rotation of generators. The electricity generated by the waves is transported to consumers via sea cable to the coast.

1.3. Wind energy

Wind power plants generate electricity through the use of kinetic energy of air [6]. A wind farm is a mast on top of which is a container with a reducer and generator. Wind blades are attached to the gearbox axis. The power plant container rotates depending on the wind direction. The main problem of wind power plants is the inconsistency of wind. This changes the generation power. Therefore, for more uniform and stable operation of the system, wind power plants for the accumulation of electricity are equipped with batteries. For the same reason, there is a need to combine wind farms into power systems and generating complexes with other methods of generating electricity.

Fig. 1.6 Wind power plant

Wind farms are used in countries with low terrain and sufficient and stable wind speeds. Germany is the world leader in the use of wind farms. More than 9,000 MW of power plants with a total capacity of more than 9,000 MW have been built here in a short period of time.

1.4. Oceanic temperature gradient

One of the types of renewable energy sources is the energy of the temperature gradient of sea water [7,8]. Its essence lies in the use of solar energy, which accumulates on the surface

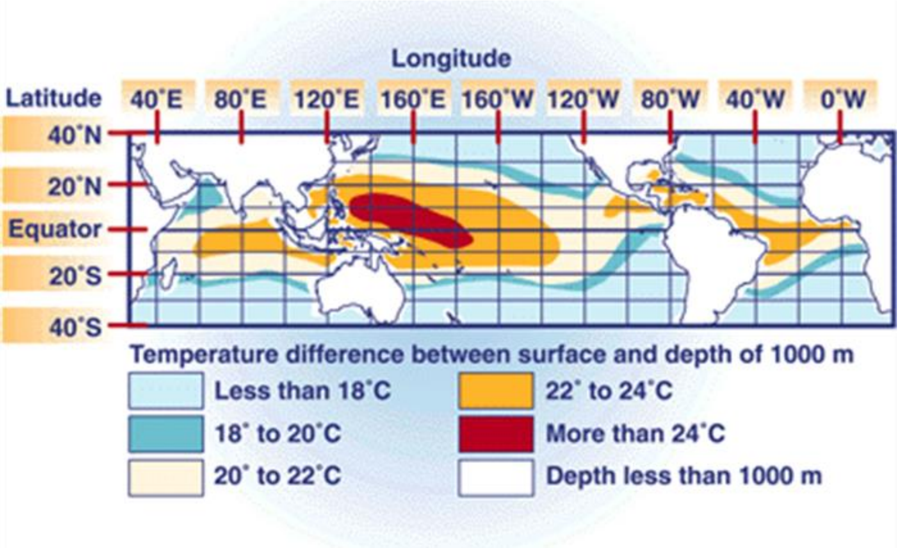


Fig. 1.7 Distribution of water temperature difference between the surface and at a depth of 1000 meters of the oceans.

World Ocean. Gradient power plants use the temperature difference at the surface and in its depth.

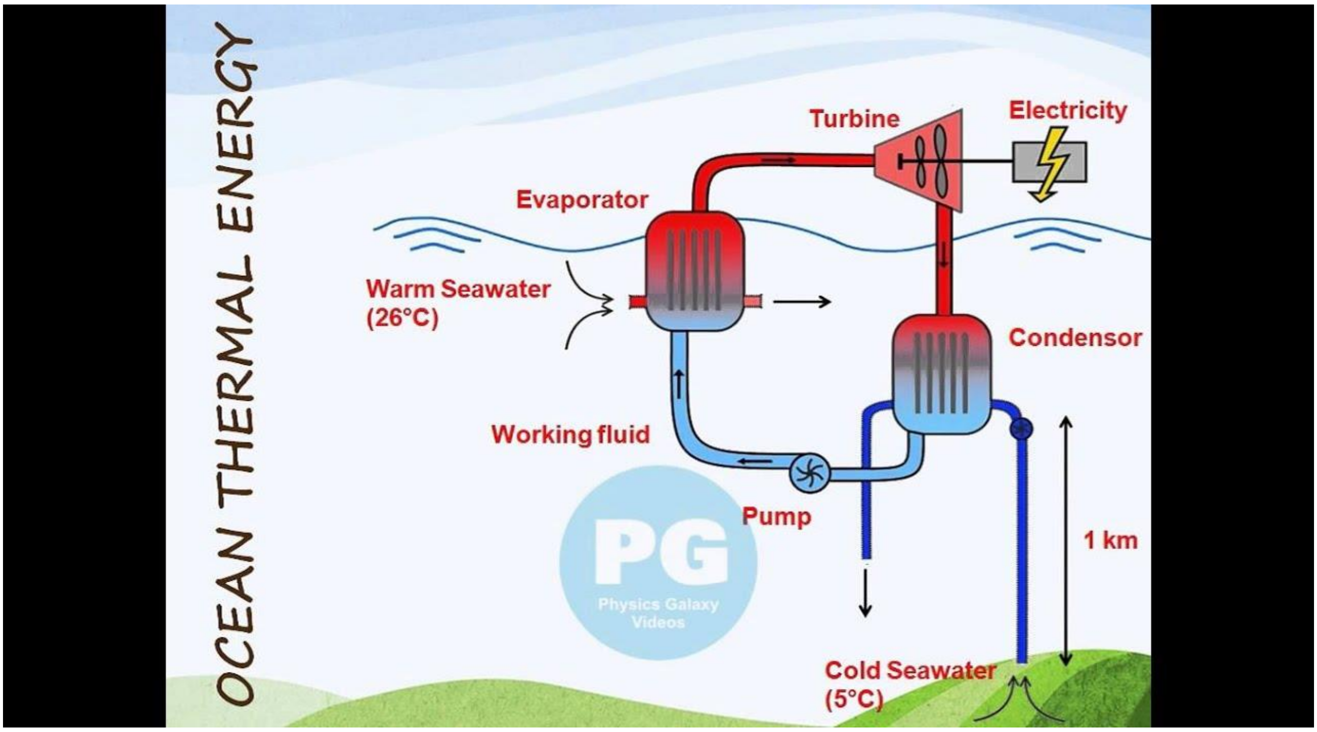


Fig. 1.8 Scheme of ocean thermal power plant

Fig. 1.8 shows the approximate distribution of water temperature difference between the surface and at a depth of 1000 meters in different locations of the oceans.

Estimates show that in the case of using 5% of the energy of the vertical temperature gradient of the tropical ocean in the area of $4 \cdot 1013$ m^2, it is possible to stably provide generating capacity up to 10000 GW.

1.5. Geothermal energy

Geothermal energy is another type of energy used to generate electricity.

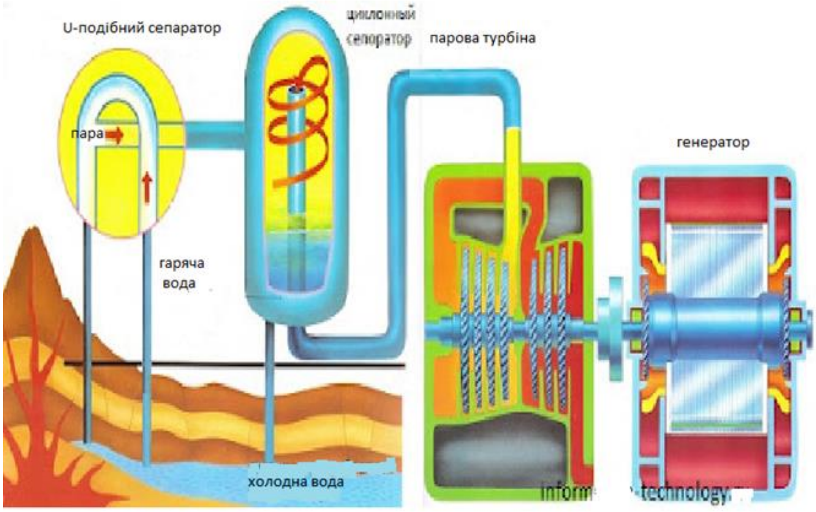


Fig. 1.9 Scheme of geothermal thermal power plant

The Earth's geothermal energy reserves are huge [9-14]. In particular, the core temperature exceeds 6000 ° C, and its cooling rate does not exceed 300-500 ° C per billion years [9,10]. Estimates show that by cooling the Earth's core by only 1 ° C, it is possible to obtain an amount of energy that is 10,000 times greater than the energy contained in all explored fossil fuels [10-12]. Using even 1% of this energy is equivalent to the operation of several hundred powerful power plants.

Fig. 1.10 Nesiavellir, Iceland. Geothermal thermal power plant

1.6. Low-potential heat engines

Stirling engineis a prominent representative of low-potential heat energy converter [15-20]. This is one of the types of heat engines, which is based on the movement of the working fluid or gaseous mixture in a closed volume. The Stirling engine is an external combustion engine. Its principle of operation is to use the energy generated by heating and cooling the working fluid. The engine was proposed in 1816 by the Scotsman Robert Stirling. However, at the turn of the XX and XXI centuries, interest in this type of heat engine erupted with renewed vigor. Currently, the world's leading companies are making new and improving old designs.

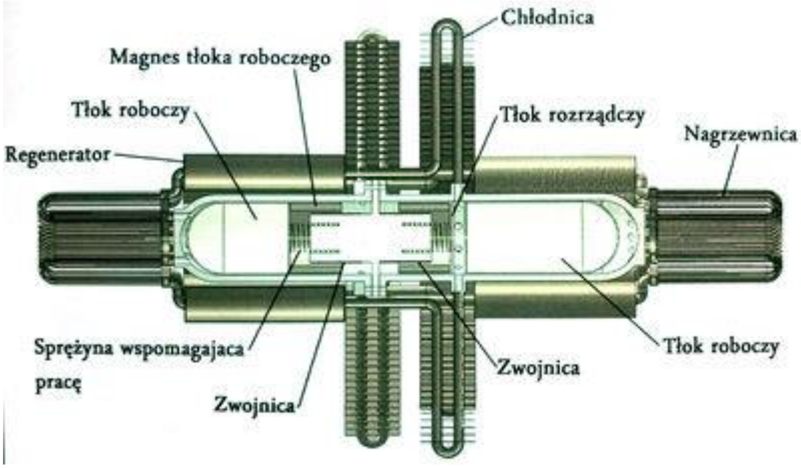


Fig. 1.11 Design of a modern Stirling engine

The design of the engine, due to the lack of various valves, camshafts and starter is very simple. Any source of thermal energy is suitable for work [19,20]. It can be solar energy, and agricultural waste, and minerals and nuclear energy. Despite the simplicity of design and absolute ubiquity, the Stirling engine is not inferior in power and performance to internal combustion engines. The reversibility of the device is also very important. It is possible to operate the Stirling engine in refrigerator mode.

Fig. 1.12 Modern Stirling engine with electric generator

The operating cycle of the device depends entirely on the heat received from the outside, and the source of this heat is not important. Given these features, it can be argued that the Stirling engine is ideal for use in solar energy.

Fig. 1.13 Industrial Stirling engine with a capacity of 1 kW

Due to the use of advanced technology for the manufacture of the device, it was possible to increase its efficiency to 65-70% of the Carnot cycle [19,20]. Stirling engines have both pros and cons. The advantages of the Stirling engine are that:

- it is practically not subject to wear, which is inherent in internal combustion engines;
- engine performance increases rapidly with increasing temperature;
- no internal combustion process, allows the device to work silently;

- it is not subject to maximum loads on the elements of the device;
- has the ability to work autonomously;
- does not require any special sources that radiate heat;
- burns fuel evenly without residue.

The disadvantages of the Stirling engine are that:

- has increased dimensions due to the fact that combustion takes place outside the inner chamber, heat is given off by a radiator;
- material-intensive engine. For productive work, it must be made of heat-resistant steel, which has low thermal conductivity, and withstands high pressure;
- requires special lubricants with a low coefficient of friction that can withstand high temperatures;
- in order to increase power, hydrogen and helium are used as the working fluid. Hydrogen is explosive, and under the action of high temperatures forms metal hydrides. Helium has a high permeability, and the leakage of the working fluid significantly reduces the working pressure.

Nitinol engine Nitinol is an alloy of nickel and titanium. In a nitrol engine, the occurrence of mechanical driving forces is based on the structural transformations of nitinol [21,22]. The crystal lattice of nitinol can be in one of two stable forms: either in the form of a volume-centered cube (BCC), or a diamond-shaped structure with centered faces (RGC). This state of the crystal lattice is called the austenitic form. The first state is called the martensitic form. The transition of BCC to RGC is called direct martensitic transformation. Inverse transition from RGC structure to BCC structure by inverse martensitic transformation. The phenomenon of the shape memory effect is based on the transformations of these crystal structures. It is also called thermoelastic martensitic transformation or martensite-austenite transition and vice versa. The hysteresis temperature of nitinol is equal to the difference between the final temperatures of austenitic-martensitic and martensitic-austenitic transformations, respectively. Given that the hysteresis temperature is 30 C, hot and cold water or hot water and the environment can be used as propellants. The nitinol-built heat engine built by R. Banks ran continuously for several months. He rotated an electric generator with a capacity of more than 0.2 kW. During operation, the engine made more than 100 thousand revolutions. The scheme of the nitinol Banks engine is shown in fig. 1.5.

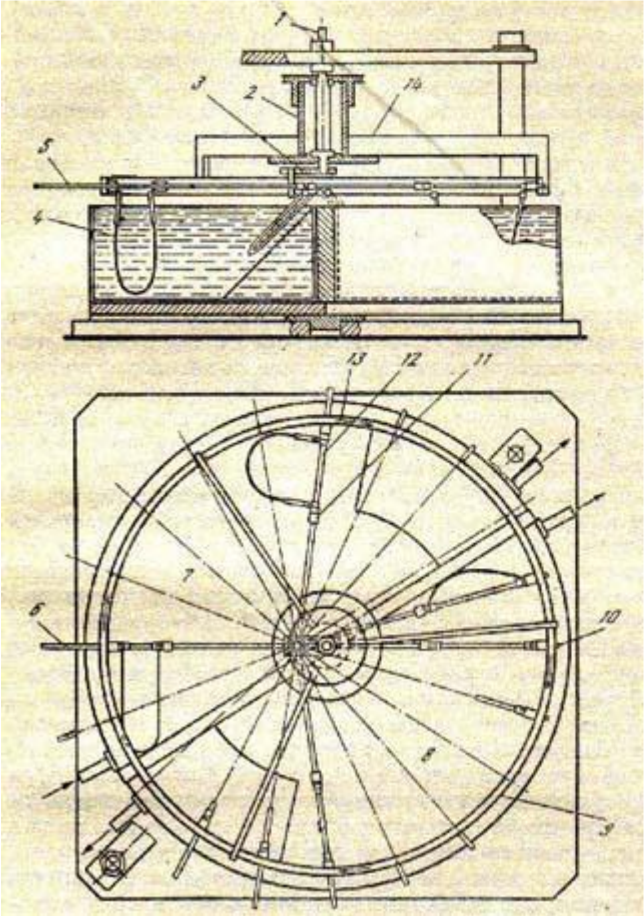


Fig. 1.14 Nitinol Banks engine

In 1982, International Innovative Technologies created an engine that had 30 nitinol loops. The cross-sectional diameter of one loop was 22 millimeters. The heater and cooler of the nitinel engine were hot water with a temperature of 55 C and ambient air with a temperature of 25 ° C. The engine speed reached 270 rpm, developing a power of 0.5 kW. The engine was highly reliable and worked flawlessly for 1.5 years [21]. An important feature of nitinol heat engines is that they, at low speeds have high torque on the shaft and at low weight develop a large specific power. This is due to the fact that the mechanical stress in nitinol is an order of magnitude greater than the pressure in the cylinders of reciprocating internal combustion engines.

Piezoelectric thermomechanical motor Piezoelectric thermomechanical motor-generator refers to thermomechanical drives that operate at low temperature gradients [23]. To convert low-potential thermal energy into mechanical piezoelectric thermomechanical motor uses both the shape memory effect and the piezoelectric effect. The engine contains a shaft mounted on rotatable supports and radially spaced nitinol levers. Nitinol levers have a shape memory effect and are connected to piezoelectric elements by electrodes. The electrodes, through a system of levers, put pressure on the piezoelectric elements and periodically deform them. The technical result is the process of direct conversion of thermal energy into mechanical energy with subsequent generation of electrical energy.

Thermoelectric pump

Thermoelectric pump (TEN) is a device that converts the thermal energy of an electrically conductive fluid into its kinetic energy [24]. It is an organic combination in one device of the electromagnetic pump and the short-circuited thermoelectric generator

Unlike electromagnetic pumps, which operate from external sources of electric current, the thermoelectric pump does not require external power. It acts due to temperature gradients. The temperature gradients required for the operation of the heating element are due to the thermal energy of the hot conductive liquid. TEN has a number of useful features:

- continuity of long work while the temperature gradient is supported;
- except for heat transfer, there is no contact with the environment;
- possibility of work in the range of temperatures from cryogenic to 2000K.

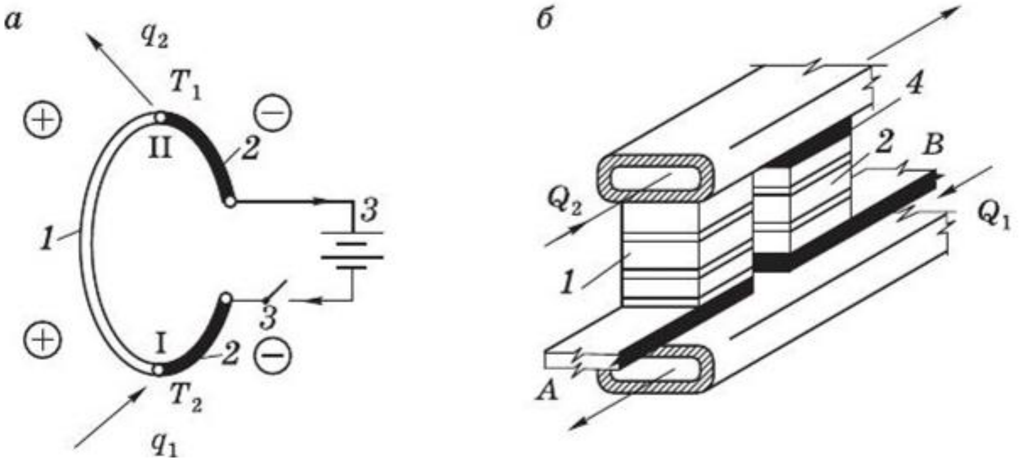


Fig. 1.15 Scheme of thermoelectric pump design.

The scheme of construction of thermoelectric heating element is shown in fig. 1.11. TEN is a short-circuited thermoelectric generator, the branches of which are connected in series by means of special switching plates. Branches 1 and 2 connected by switching plates form joints. As a result, a group of hot junctions operating at a temperature of T1 and cold junctions with an operating temperature of T2 are formed. The total EMF of the developing TEN is equal to the sum of the EMF of the individual elements. When the poles of the heating element are closed, thermoelectric current passes through the thermoelectrodes and switching plates. Since the liquid working fluid is in an external magnetic field (the magnetic system is not shown in the diagram), it is affected by the Ampere force, which drives it.

2. DESIGN SECTION

2.1 Method of electrothermal analogy

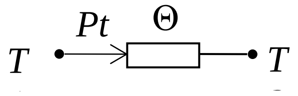
The calculation of the thermal regime of the converter can be performed using the formal similarity of the equations of electrical conductivity and thermal conductivity [25,26]. Guided by the principle of similarity, the heat transfer process can be represented in the form of a thermal circuit, the elements of which are heat sources, heat receivers and thermal supports, which are in the way of heat distribution from the source to the receiver. In this case, each node of the thermal circuit is assigned a certain temperature T. Heat fluxes and temperature differences in the thermal circuit are variables and are described by Ohm's and Kirchhoff's laws for thermal circuits. Formally, they are similar to Ohm's and Kirchhoff's laws for electric circuits. Based on these laws, thermal circuits can be transformed and calculated.

The heat that is supplied to the hot junctions of the TEG by conduction is transferred to the radiator, and then by convection - to the environment.The flow of heat traveling from a node with a temperature of T1 to a node with a temperature of T2 is a fair Ohm's law

$$P_t = \frac{\Delta T}{\Theta}, \tag{2.1}$$

here - $\Delta T = T_1 - T_2$ - temperature difference between the ends,

Θ -thermal resistance of the circuit.



Thermal resistance is described by the formula:

$$\Theta = \frac{1}{\kappa}\frac{\Delta l}{\Delta S}, \tag{2.2}$$

where κ - specific coefficient of thermal conductivity;

ΔS - cross-sectional area of the branch,

Jul- the length of the heat-conducting branch.

The temperature difference between the ends of several series-connected branches of a thermal circuit is described by Kirchhoff's second law

$$T_1 - T_2 = \Delta T = \sum_{i=1}^{n} \Delta T_i \ , \tag{2.3}$$

where

$$\Delta T_i = \Theta_i P_t ,$$

- temperature difference on the i-th branch.

Thermal resistance of series-connected branches

$$\Theta = \sum_{i=1}^{n} \Theta_i \tag{2.4}$$

where

$$\Theta_i = \frac{1}{\kappa} \frac{\Delta l_i}{\Delta S_i} ,$$

- thermal resistance and - that branch.

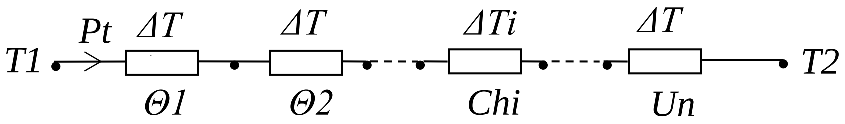


Fig. 2.1 - Thermal circuit of series connection of thermal resistances

The flow of heat from a section of a circle with temperature T1 to a section with temperature T2 on several branches is described by Kirchhoff's first law for heat flows:

$$P_t = \sum_{i=1}^{n} P_{ti} \ , \tag{2.5}$$

where the heat flow in the i-th branch

$$P_{ti} = \frac{\Delta T}{\Theta_i} . \tag{2.6}$$

So,thermalresistance of parallel connected branches

$$\Theta = \left(\sum_{i=1}^{n} \frac{1}{\Theta_i} \right)^{-1} . \tag{2.7}$$

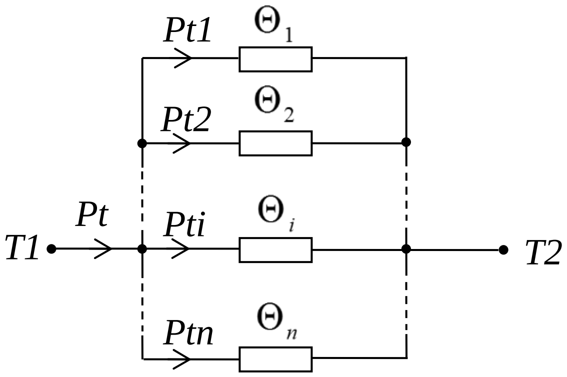


Fig. 2.2 - Thermal scheme of parallel connection of thermal resistances

The flow of the convective component of the heat flux is described by the ratio:

$$P_c = \alpha \ S \ \Delta T\ , \tag{2.8}$$

where: α is the convective heat transfer coefficient;

S- radiator surface area;

ΔT - temperature difference between radiator and medium temperatures.

Sizethermalresistanceheat exchange with the medium by convection is describedratio [26]:

$$\Theta_c = \frac{1}{\alpha}\frac{1}{\Delta S}\ , \tag{2.9}$$

Generalthermalthe resistance of the radiator can be reduced to two components: conduction, which depends on the thermal conductivity of the radiator, and convection, which is determined by the heat dissipation capacity of the radiator surface.

Convection heat transfer coefficient α depends on many factors, especially the position of the cooling surface in space. In particular, for the flat surface of the radiator, oriented horizontally heated surface up the coefficient of convective heat transfer

$$\alpha = 1.3A\frac{\sqrt[4]{T_r - T_a}}{h} \tag{2.10}$$

For a flat surface of the radiator oriented vertically:

$$\alpha = A\frac{\sqrt[4]{T_r - T_a}}{h} \tag{2.11}$$

If the radiator is isolated, away from other heat sources, the value is $\alpha = 3 \div 20\ Bm/м^2К$. For cooling systems with forced blowing $\alpha = 100 \div 1000\ Bm/м^2К$.

2.2 Thermoelectric effects

Seebeck effectis the basis of the thermoelectric generator [26]. It consists in the fact that in an open electric circuit, which consists of two different types of semiconductors connected in series, there is a thermoEMF. This connection is called a thermocouple, or thermocouple. Materials of the same chemical composition, but with different types of conductivity, are considered to be different types. Qualitatively, the Seebeck effect is described as follows. If the ends of the n-type semiconductor are maintained at different temperatures T1 and T2, the electrons at the hot end will have more energy and velocity than at the cold. In addition, in a semiconductor with increasing temperature, the concentration of free electrons increases and will be higher at the hot end than at the cold end. As a result, an electron flow will occur in the electron semiconductor in the direction from the hot to the cold end. At the same time, a negative charge will accumulate on the cold end. The process of charge accumulation will continue until the resulting potential difference causes a secondary flow of electrons in the opposite direction, which is equal to the primary. The thermoEMF coefficient can be found from the ratio:

$$\alpha = \frac{k}{e}\left(\frac{\varepsilon}{kT} - \varsigma\right),$$

where k - Boltzmann constant, e - electron charge, ε - average electron energy, $\varsigma = \eta/kT$ - reduced chemical potential, η - chemical potential of electrons.

The described phenomenon in hole semiconductors proceeds similarly, with the difference that in hole semiconductors on the cold end positive charges accumulate. Therefore, in the thermocouple, which consists of series-connected semiconductor branches with hole and electronic conductivity type, the thermoEMF of the branches is added. The total thermoEMF of the thermocouple is determined by the ratio.

$$E_{te} = (\alpha_n + \alpha_p)(T_1 - T_2) = \alpha_{pn}(T_1 - T_2), \tag{2.1}$$

where α_p - coefficient of thermoEMF of the p-type branch,

α_n - the thermoEMF coefficient of the n-type branch,

$\alpha_{pn} = \alpha_p + \alpha_n$ - thermoEMF coefficient of the thermocouple.

Peltier effect[27] is that when passing direct current through a thermocouple, at the point of contact of semiconductors, a certain thermal power is released or absorbed (depending on the direction of current)

$$P_{П} = ПI\,, \tag{2.2}$$

here P = αT is the Peltier coefficient,

T- contact temperature,

AND- amperage.

The cause of Peltier heat is the transition of electrons through contact in the direction from p-type to n-type material. At the same time, they overcome the potential barrier and take away energy at the point of contact, with contactcooled. When changing the direction of the current to the opposite at the point of contact in addition to the heat of Joule will be released Peltier heat. The Peltier effect is a surface effect.

2.3 Energy calculation of the thermocouple

If a load in the form of an external resistance R is connected to the thermocouple, an electric current will appear in the circuit [28]. The magnitude of the current is found from Ohm's law for a complete circle

$$I = \frac{E_{te}}{R + r_{te}}\,, \tag{2.3}$$

where $r_{te} = r_p + r_n + r_k$ -internal resistance of the thermocouple,

*rp*and rn support of branches of p and n-type conductivity, respectively,

r_k - resistance of switching plates,

$R + r_{te}$- total resistance of the thermoelectric circuit.

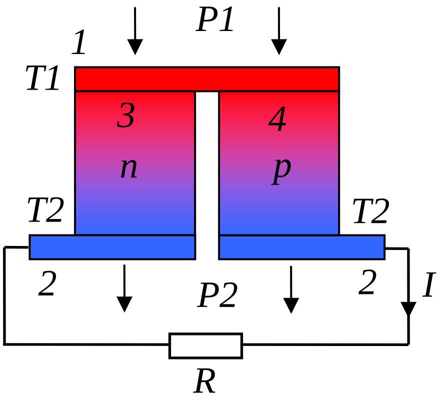


Fig. 2.3 Scheme of thermocouple with load resistance.

1 and 2 - cold and hot heat collectors, 3 and 4 - branches of thermocouple n- and p-type conductivity.

If we express the switching resistance in the form of a relative value

$$m_\rho = \frac{r_k}{r_p + r_n}, \tag{2.4}$$

and the supports of the branches due to their geometric dimensions and specific supports of thermoelectric materials, then

$$r_{te} = (\rho_p + \rho_n)(1 + m_\rho)\frac{l}{S}, \tag{2.5}$$

where ρp and ρn are the specific supports of the branches of p and n-types, respectively, *l*- length of branches,

S- cross-sectional area of branches.

It is advisable to record the load resistance in the form

$$M = \frac{R}{r_{te}}, \qquad (2.6),$$

then formula (2.3) will take the form

$$I = \frac{E_{te}}{r_{te}} \frac{1}{(M+1)}, \tag{2.7}$$

and the voltage on the external resistance

$$U = E_{te} \frac{M}{(M+1)}. \tag{2.8}$$

Find the useful electric power generated by the TEG

$$P_{te} = UI = \frac{E_{te}^{\;2}}{r_{te}} \frac{M}{(M+1)^2} = \frac{\alpha_{pn}^2 (\Delta T)^2}{(1+m_\rho)(\rho_p + \rho_n)\frac{l}{S}}. \tag{2.9}$$

The operation of a thermoelectric generator, like any heat engine, is described by the formulas of thermodynamics. Therefore, it can be called not only a thermoelectric but also a thermodynamic device. To consider the operation of the TEG from a thermodynamic point of view, it is necessary to express the temperature difference and its geometric dimensions through the heat fluxes in the thermocouple. In the absence of current under the condition of adiabatic insulation of the side faces of the branches, the conductive heat flow through the thermocouple is determined by the thermal conductivity of both branches. According to Fourier's law at the temperature difference ΔT

$$P_\kappa = \Delta T (\kappa_p + \kappa_n) \frac{S}{l}. \tag{2.10}$$

where κ_p and κ_n are the coefficients of thermal conductivity of p and n-type branches, respectively.

In the presence of current in the volume of both branches, the Joule power is released

$$P_j = I^2 r_{te}. \tag{2.11}$$

In addition to these flows, the hot junction is absorbed

$$P_1^{\Pi} = I\alpha_{pn} T_1, \tag{2.12}$$

and Peltier's heat is released at the cold junction

$$P_2^{\Pi} = I\alpha_{pn} T_2, \tag{2.13}$$

Let's assume that half of Joule's power goes to hot and half to cold junction. Then the power balance at the hot and cold junctions of the thermocouple will look like

$$P_1 = P_1^{\Pi} + P_\kappa - \frac{1}{2} P_j, \tag{2.14}$$

$$P_2 = P_2^{\Pi} + P_\kappa + \frac{1}{2} P_j, \tag{2.15}$$

Since the Fourier heat flux does not depend on the current, it is convenient to express the heat fluxes P$_1$ and P$_2$ in P$_k$

$$\frac{P_1}{P_\kappa}=1+\frac{\alpha_{pn}^2}{\left(\kappa_p+\kappa_n\right)\left(\rho_p+\rho_n\right)\left(1+m_\rho\right)}\frac{1}{M+1}\left[T_1-\frac{\Delta T}{2(M+1)}\right], \quad (2.16)$$

$$\frac{P_2}{P_\kappa}=1+\frac{\alpha_{pn}^2}{\left(\kappa_p+\kappa_n\right)\left(\rho_p+\rho_n\right)\left(1+m_\rho\right)}\frac{1}{M+1}\left[T_2-\frac{\Delta T}{2(M+1)}\right], \quad (2.17)$$

Size

$$z=\frac{\alpha_{pn}^2}{\left(\kappa_p+\kappa_n\right)\left(\rho_p+\rho_n\right)}, \quad (2.18)$$

which depends only on the material properties of semiconductor branches is called the thermoelectric quality factor of the material, and the value

$$z_{te}=\frac{z}{\left(1+m_\rho\right)}, \quad (2.19)$$

thermoelectric quality factor of the thermocouple.

Due to the law of conservation of energy, the electric power generated by a thermocouple is found as the difference between the supplied and removed heat flows

$$P_{te}=P_1-P_2. \quad (2.20)$$

Using (2.16) and (2.17) we find the efficiency of the thermocouple as the ratio of useful electric power to the supplied

$$\eta=\frac{P_{te}}{P_1}=\frac{\Delta T}{T_1}\frac{M/(M+1)}{1+\frac{M+1}{z_{te}T_1}-\frac{\Delta T}{2T_1}\frac{1}{M+1}}. \quad (2.21)$$

The first factor describes the efficiency of a heat engine operating on the Carnot reversal cycle, and the second takes into account its reduction due to irreversible losses due to the thermal conductivity of the thermoelectric material and the release of Joule heat.

To obtain the maximum useful power depending on the load resistance, it is necessary to solve the equation

$$\frac{dP_{te}}{dM}=\frac{E_{te}^2}{r_{te}}\frac{d}{dM}\left(\frac{M}{(M+1)^2}\right)=0. \quad (2.22)$$

Obviously the maximum power

$$P_{te}^{\max} = \frac{E_{te}^{\ 2}}{4r_{te}} \tag{2.23}$$

is achieved at M = 1, which corresponds to the equality of the load resistance to the internal resistance of the thermocouple $R = r_{te}$. The value of efficiency will be the value

$$\eta_P = \frac{\Delta T}{T_1}\frac{1}{4/(z_{te}T_1) + 2 - \Delta T/2T_1}\,. \tag{2.24}$$

In addition to the maximum power mode, the thermocouple can operate in the maximum efficiency mode. Maximum efficiency [28]

$$\eta_{\max} = \frac{\Delta T}{T_1}\frac{M_0 - 1}{M_0 + T_2/T_1}\,, \tag{2.25}$$

is from the equation

$$\frac{d\eta_{te}}{dM} = 0\,, \tag{2.26}$$

at

$$M_0 = \sqrt{1 + z_{te}T_c}\,, \tag{2.27}$$

where $T_c = (T_1 + T_2)/2$ - average temperature.

2.4 Features of short-circuit thermoelectric generator

A traditional thermoelectric generator consists of a large number of thermocouples connected in series and in parallel.

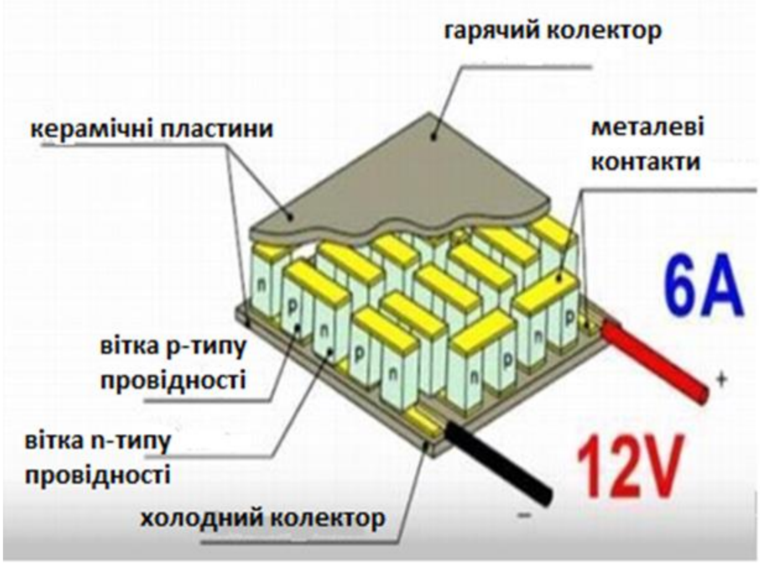


Fig. 2.4 - Scheme of a traditional thermoelectric generator.

Each of the thermocouples is in contact with hot and cold metal heat collectors. At the same time in a place of contact there are parasitic thermal support.

A short-circuited thermoelectric generator consists of only two branches of n- and p-type conductivity, ie only one thermocouple [27]. The area of the branches can reach the area of the panel battery.

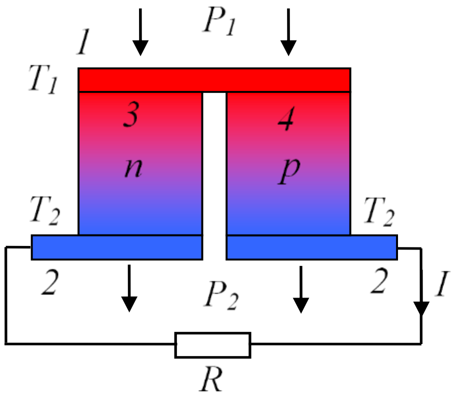


Fig. 2.5 Scheme of short-circuited TEG. 1 and 2 - cold and hot heat collectors, 3 and 4 - branches of thermocouple n- and p-type conductivity.

As a result, the thermocouple has a large area and very low electrical resistance. As a result, at low lasing voltage (hundredths of a volt), it is possible to obtain currents in the hundreds and thousands of amperes [27,28].

Short-circuited TEGs are mainly used to power thermoelectric pumps, electromagnets, low-voltage to high-voltage converters, etc. In short-circuited TEG, the source of electricity generation and consumption are integrated in one electrical device. To ensure the temperature regime of the TEG branches, an active or passive cooling system is connected to it. In the short-circuit design of the TEG, the direction of the electric current coincides with the direction of the heat flow. The peculiarity of short-circuited TEGs is that they do not have switching joints and layers of electrical and thermal insulation. Housing and mounting parts in this case are both conductors of heat and electricity.

Temperature and energy level of low-potential surface energy sources are given in table 2.1.

Sources of low-potential heat Table 2.1

TYPE OF LOW-TEMPERATURE HEAT SOURCE					
Natural heat sources	Temperature level of the source ^{o}C	Energy and source level , MBT	Man-made heat sources	Temperature level of the source, ^{o}C	Source energy level, MBT
Water surface soil geothermal	4 … 18 6 … 15 35 … 70	0.9 … 51.6 1 … 2 0.29 … 3	Water : sewage technical technology	10 … 17 15 … 30 40 … 70	0.3 … 90 2.4 … 10.6 0.3 … 22.1
Air	-5 …20	0.3 … 3	Air	0 … 50	0.3 … 22.1
Soil environment	4 .. 12	0.1 … 5.9	-	-	-
Solar radiation	0 …75	0.1 … 150	-	-	-

The cross section of the mounting in relation to the cross section of the semiconductor is selected so that the loss of electric current through the closing circuit does not exceed 5-10%. Heat sources in short-circuited TEGs can be molten coolants, radioisotopes, fuel elements of the nuclear reactor, etc .. Reliable thermal and electrical contacts of the semiconductor with the material of the heat pipe and housing are provided by pressing, welding or soldering through appropriate gaskets. Short-circuited TEG can be cooled by both radiators and liquid circulating in the tubes penetrating the TEG structure.

Advantages of short-circuit design of TEG - increase of thermodynamic efficiency of the generator due to absence of switching and insulating layers. In the future, they can be used in heat generators with a capacity of hundreds and thousands of kilowatts.

3 CALCULATION OF CONVERTER PARAMETERS

3.1 Structure and principle of operation

The principle of operation of the thermoelectromechanical low-potential converter is explained by the scheme shown in Figure 3.1. In particular, the ferromagnetic disk (rotor) is movably mounted in a cylindrical housing (stator) so that it can rotate around the conductive axis. In the rotor, using a magnetic system (to simplify the drawing, the magnetic system is not shown in the diagram), in the direction perpendicular to its cross section, the magnetic field is excited by induction B. Electric current produced by a short-circuited thermocouple through low-resistance liquid metal contacts on the ferromagnetic rotor. Due to the cylindrical symmetry of the rotor, the current flows radially. The resulting Ampere force Fa causes the rotor to rotate. The direction of rotation is determined by the rule of the left hand,

$$F_a = IBr\,, \tag{3.1}$$

where I is the radial current in the rotor,B -magnetic induction, r - rotor radius.

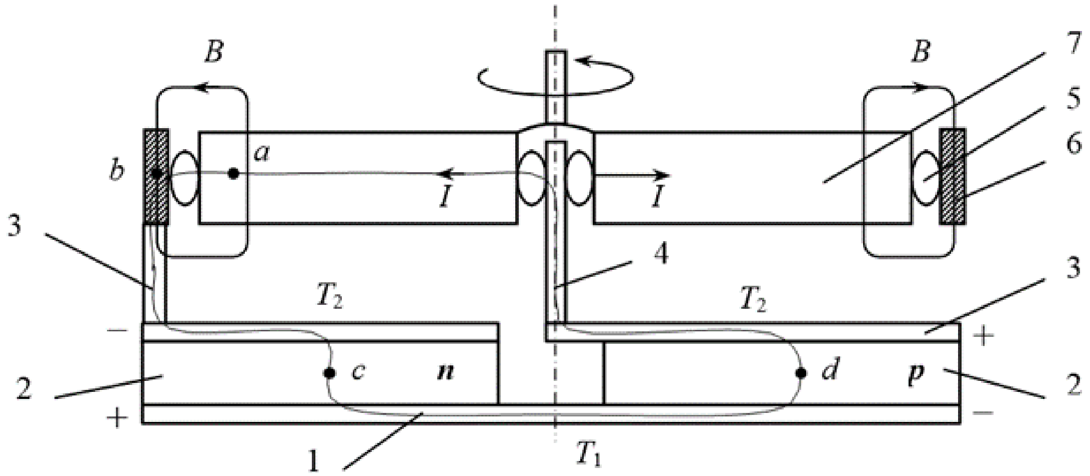
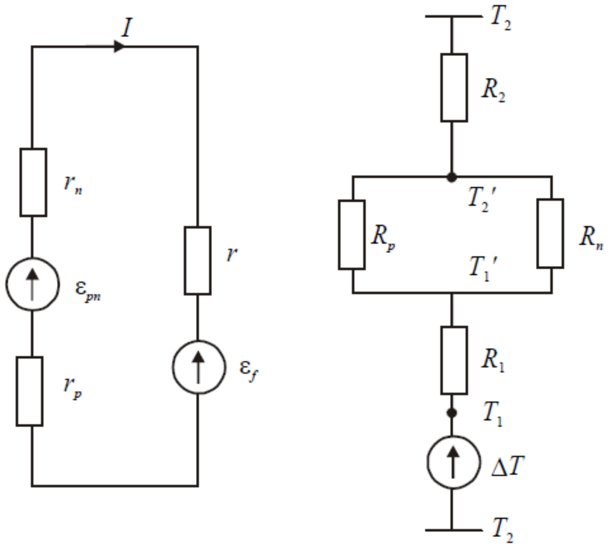


Fig. 3.1 Scheme of thermoelectromechanical low-potential heat energy converter. 1 - collector, 2 - thermocouples of hole and electronic types of conductivity, 3 - copper switching bus, 4 - conductive axis of rotation, 5 - low-resistance liquid metal contacts, 6 - stator, 7 - ferromagnetic rotor.

3.2 Calculation of thermal regime

In the converter circuit, as a heat engine, the heat source is characterized by a given temperature difference ΔT.



a) б)

Fig. 3.2. Equivalent electrical (a) and thermal (b) converter circuits: r_p - electrical resistance of the hole type hole conductivity, r_n - electrical resistance of the electronic conductivity type branch, r - total resistance of collectors, switching buses, ferromagnetic rotor and liquid metal low-impedance contacts, ε_{pn}- thermoEMF of the thermocouple, ΔT is the temperature difference between the heater and the refrigerator, Θ_1 is the thermal resistance between the heater and the hot junction of the thermocouple, Θ_p and Θ_n is the thermal resistancebranch hole and electronic conductivity types, Θ_2 - thermal resistance between the refrigerator and the cold junction of the thermocouple.

Current-generating branches of electronic and hole type conductivity are connected in parallel in the form of two independent thermal resistances Θ_n and Θ_p between the heater, which is characterized by temperature T_1 and the refrigerator (environment), which has a temperature of T_2. The thermal resistances of the elements change. They decrease with increasing operating current flowing in the electrical circuit of the thermocouple. Thermal contact supports, on which from the point of view of current generation some part of the available thermal difference ΔT is unproductively spent, are shown in the figure in the form of thermal resistances Θ_1 and Θ_2 connected in series with the branches.

Using the method of electrothermal analogy and the equivalent thermal circuit of the converter, we find the thermal resistance between the heater and the refrigerator

$$\Theta = \Theta_1 + \Theta_2 + \Theta_{pn}, \tag{3.2}$$

where

$$\Theta_{pn} = \frac{\Theta_p \Theta_n}{\Theta_p + \Theta_n},$$

- equivalent resistance of parallel connection of thermal resistances,

Find the temperature difference between the junctions

$$\Delta T' = \Delta T \frac{\Theta_{pn}}{\Theta_1 + \Theta_2 + \Theta_{pn}} = \frac{\Delta T}{(1 + m_\kappa)}, \tag{3.3}$$

where ΔT = T_1-T_2, T_1 and T_2- temperature of the heater and refrigerator,$\Delta T'$= T1′- T2′, T1′ and T2′ - temperature of hot and cold junctions, respectively, $m_\kappa = (\Theta_1 + \Theta_2)/\Theta_{pn}$ coefficient that describes heat loss at switching and insulating junctions.

Obviously, due to heat loss, the temperature difference between the joints is smaller than the temperature difference between the heater and the refrigerator.

3.3 Calculation of electromechanical parameters

We will consider the thermoelectric converter as a kind of current-generating pn pair, the feature of which is that it has no traditional active resistance connected to the positive and negative poles of the p-n pair. The role of resistance is performed by Faraday induction anti-EMF, which occurs in an electric circuit when rotating in the magnetic field of the converter rotor, and is directed toward the thermoelectric current. To calculate the parameters of the converter, we will use equivalent substitution schemes: equivalent electrical (Fig. 2a) and equivalent thermal (Fig. 2b), which are built on elements with concentrated parameters.

The operation of the converter is described by Maxwell's second equation and the generalized Ohm's law [16, 24]

$$\oint \vec{E} d\vec{l} = -\frac{\partial \Phi}{\partial t}, \tag{3.4}$$

$$\vec{j} = \sigma \vec{E} - \alpha \sigma \nabla T, \tag{3.5}$$

where E is the electric field strength, F = BSr is the magnetic flux that passes through the cross section of the rotor, $S_r = \pi r^2$ - cross-sectional area of the rotor, r is the radius of the rotor, B is the magnetic induction in the rotor, j is the current density, σ and α, respectively, the coefficients of conductivity and thermoEMF of the thermocouple branches, ∇T- temperature gradient in the thermocouple.

Integrating (3.4) along the contour abcda and using equations (3.3) and (3.5) we obtain

$$I\left(r_{pn}+r\right)-\frac{\alpha_{pn}\Delta T}{\left(1+m_{\kappa}\right)}=\varepsilon_{f}, \tag{3.6}$$

where I is the current in the circuit, $r_{pn} = r_p + r_n$, $\alpha_{pn}=\alpha_p+\alpha_n$, α_p and α_n- thermoEMF coefficients of thermocouple branches.

Find the EMF of Faraday induction

$$\varepsilon_{f}=-\frac{\partial \Phi}{\partial t}=-\frac{\partial}{\partial t}\left(BS_{r}\right)=-B\frac{\partial S_{r}}{\partial t}=-B\pi r^{2}n=-nBS_{r}=-\Phi n \tag{3.7}$$

where $\varepsilon_f = -\Phi n$ - EMF of Faraday induction, n - rotor speed.

Using (3.7), formula (3.6) is represented as

$$Ir_{pn}(1+m_{\sigma})-\frac{\alpha_{pn}\Delta T}{1+m_{\kappa}}=-\Phi n, \tag{3.8}$$

where $m_{\sigma}=r/r_{pn}$ - coefficient of electrical losses, which describes the loss of electrical energy in electrical insulation and switching junctions, $m_{\kappa}=\left(\Theta_{1}+\Theta_{2}\right)/\Theta_{pn}$ - coefficient of heat loss, which describes the loss of heat energy on contact thermal resistances.

In the "idle" mode, the rotor speed reaches the maximum value, and the induction caused by it against EMF completely compensates for thermoEMF. In this case, there is no current in the circuit. If I = 0, then we obtain from (3.8)

$$n_{\max}=\frac{\alpha_{pn}\Delta T}{\Phi}\frac{1}{1+m_{\kappa}}. \tag{3.9}$$

In the "short circuit" mode, when the rotor is stationary, the current in the circuit reaches its maximum value

$$I_{\max}=\frac{\alpha_{pn}\Delta T}{r_{pn}}\frac{1}{(1+m_{\sigma})(1+m_{\kappa})}. \tag{3.10}$$

Using (3.6) and (3.7), from formula (3.8) we find the speed of the converter rotor

$$n=\frac{\alpha_{pn}\Delta T}{\Phi(1+m_{\kappa})}(1-S), \tag{3.11}$$

where

$$S = \frac{n_{\max} - n}{n_{\max}}, \tag{3.12}$$

slip coefficient - introduced by analogy with the slip coefficient in the theory of asynchronous machines.

Given (3.11) from (3.8) we find the current

$$I = \frac{\alpha_{pn}\Delta T}{r_{pn}} \frac{1}{(1+m_{\sigma})(1+m_{\kappa})} S . \tag{3.13}$$

As can be seen from equations (3.11) and (3.12) at $n = n_{\max}$, slip S = 0 and increases proportionally with decreasing rotor speed. The maximum value of S = 1 is reached when $n = 0$.

Find the mechanical power of the converter as a product of EMF induction on current

$$P = I\Phi\mathrm{n} = \frac{(\alpha_{pn}\Delta T)^2}{r_{pn}(1+m_{\sigma})(1+m_{\kappa})^2} S(1-S). \tag{3.14}$$

We find the maximum power from the condition dP/dS = 0.

$$\frac{dP}{dS} = \frac{(\alpha_{pn}\Delta T)^2}{r_{pn}(1+m_{\sigma})(1+m_{\kappa})^2}(1-2S) = 0,$$

where it is seen that the maximum is achieved at S_P = 1/2.

For maximum power we get:

$$P_{\max} = \frac{(\alpha_{pn}\Delta T)^2}{4r_{pn}(1+m_{\sigma})(1+m_{\kappa})^2} \tag{3.15}$$

It is known that the electromagnetic moment

$$M = \frac{P}{2\pi n},$$

therefore, for the electromagnetic moment of the converter we obtain

$$M = \frac{\alpha_{pn}\Delta T\Phi}{2\pi r_{pn}(1+m_{\sigma})(1+m_{\kappa})} S . \tag{3.16}$$

At S = 1,

$$M_{\max} = \frac{\alpha_{pn}\Delta T\Phi}{2\pi r_{pn}(1+m_{\sigma})(1+m_{\kappa})} .$$

As can be seen from the obtained relations, the amount of mechanical power does not depend on the magnetic flux. This is obvious, because the electromagnetic torque of the rotor is proportional, and the speed is inversely proportional to the magnetic flux. At the same time, the mechanical power is determined by the product of these parameters.

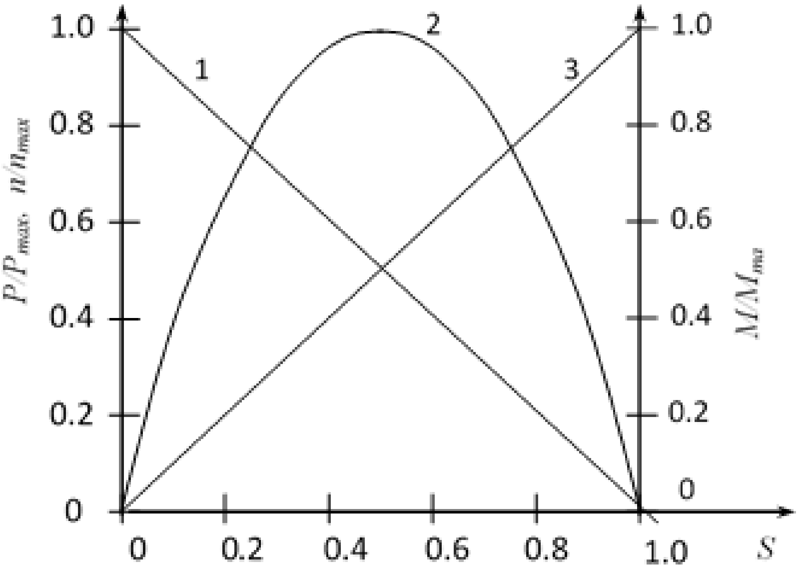


Fig. 3.3 Dependence of electromechanical parameters of the converter on sliding. Curve 1.- n / nmax, 2. - P / Pmax, 3. - M / Mmax.

Obviously, the maximum power in the range of optimal: stpym, electromagnetic moment and frequency of rotation:

$$I_P = \frac{\alpha_{pn}\Delta T}{2r_{pn}} \frac{1}{(1+m_\sigma)(1+m_\kappa)}, \tag{3.17}$$

$$M_P = \frac{\alpha_{pn}\Delta T\Phi}{4\pi r_{pn}} \frac{1}{(1+m_\sigma)(1+m_\kappa)}, \tag{3.18}$$

$$n_P = \frac{\alpha_{pn}\Delta T}{2\Phi} \frac{1}{(1+m_\kappa)}. \tag{3.19}$$

3.4 Calculation of thermodynamic efficiency

The operation of the converter, like any heat engine, is described by the formulas of thermodynamics. Therefore, it can be called not only a thermoelectric but also a thermodynamic device. To consider the work of TEMC from a thermodynamic point of view, it is necessary to express the temperature difference and geometric dimensions of semiconductor branches through heat fluxes in the thermocouple. In the absence of current under the condition of adiabatic insulation of the side faces of the branches, the conductive heat flow through the thermocouple is determined by the thermal conductivity of both branches. According to Fourier's law, the temperature difference ΔT

$$P_\kappa = \Delta T\left(\kappa_p + \kappa_n\right)\frac{Q}{l}. \tag{3.20}$$

where Q and l are the cross-sectional area and height of the branches, κp and κn are the coefficients of thermal conductivity of the branches.

In the presence of current in the volume of both branches, Joule heat is released

$$P_j = I^2 r_{pn}\left(1 + m_\sigma\right). \tag{3.21}$$

In addition to the heat of Joule, the hot junction is absorbed

$$P_1^\Pi = I\alpha_{pn}T_1, \tag{3.22}$$

and Peltier's heat is released at the cold junction

$$P_2^\Pi = I\alpha_{pn}T_2. \tag{3.23}$$

Let's assume that half of Joule's power goes to hot and half to cold junction. Then the power balance at the hot and cold junctions of the thermocouple will look like

$$P_1 = P_1^\Pi + P_\kappa - \frac{1}{2}P_j, \tag{3.24}$$

$$P_2 = P_2^\Pi + P_\kappa + \frac{1}{2}P_j, \tag{3.25}$$

Since the Fourier heat flux does not depend on the current, it is convenient to express the heat fluxes P$_1$ and P$_2$ in P$_k$

$$\frac{P_1}{P_\kappa} = 1 + \frac{\alpha_{pn}^2}{\left(\kappa_p + \kappa_n\right)\left(\rho_p + \rho_n\right)}S\left[T_1 - \frac{\Delta T}{2}S\right], \tag{3.26}$$

$$\frac{P_2}{P_\kappa} = 1 + \frac{\alpha_{pn}^2}{\left(\kappa_p + \kappa_n\right)\left(\rho_p + \rho_n\right)}S\left[T_2 - \frac{\Delta T}{2}S\right], \tag{3.27}$$

Size

$$z = \frac{\alpha_{pn}^2}{\left(\kappa_p + \kappa_n\right)\left(\rho_p + \rho_n\right)}, \tag{3.28}$$

which depends only on the material properties of semiconductor branches is called the thermoelectric quality factor of the material.

Due to the law of conservation of energy, the electric power generated by a thermocouple is found as the difference between the supplied and removed heat flows

$$P = P_1 - P_2. \tag{3.29}$$

Find the efficiency of the thermocouple as the ratio of useful electric power to the supplied

$$\eta = \frac{P_1 - P_2}{P_1} = \frac{\Delta T}{T_1} \frac{S(1-S)}{(zT_1)^{-1} + S - S^2(\Delta T / 2T_1)} \tag{3.30}$$

The first factor describes the efficiency of a heat engine operating on the Carnot reversal cycle, and the second takes into account its reduction due to irreversible losses due to the thermal conductivity of the thermoelectric material and the release of Joule heat.

In the mode of maximum mechanical power at S = 1/2 with (3.31) we obtain

$$\eta_p = \eta_\kappa \frac{1}{4(zT_1)^{-1} + 2 - \Delta T / 2T_1} \tag{3.32}$$

In addition, the converter can operate in maximum efficiency. The optimal value of the slide at which this mode is achieved, we find from the condition

$$\frac{d\eta}{dS} = 0. \tag{3.33}$$

$$S_0 = \frac{1}{1 + \sqrt{1 + zT}}, \tag{3.34}$$

where *T*= (T1 + T2)/2 - average temperature.

The maximum value of efficiency at S = S_0 is determined by the formula

$$\eta_p = \eta_\kappa \frac{1}{1 + 2(1 + \sqrt{1 + zT})(zT_1)^{-1}} \tag{3.35}$$

In the range of maximum efficiency, the power, electromagnetic moment and frequency of rotation are optimal, to be described by the ratios:

$$P_\eta = \frac{(\alpha_{pn}\Delta T)^2}{r_{pn}(1+m_\sigma)(1+m_\kappa)^2} S_0(1-S_0)\,. \tag{3.36}$$

$$M_\eta = \frac{\alpha_{pn}\Delta T \Phi}{2\pi r_{pn}(1+m_\sigma)(1+m_\kappa)} S_0\,. \tag{3.37}$$

$$n_\eta = \frac{\alpha_{pn}\Delta T}{\Phi(1+m_\kappa)}(1-S_0)\,, \tag{3.38}$$

where

$$S_0 = \frac{1}{1+\sqrt{1+zT}}\,, \tag{3.39}$$

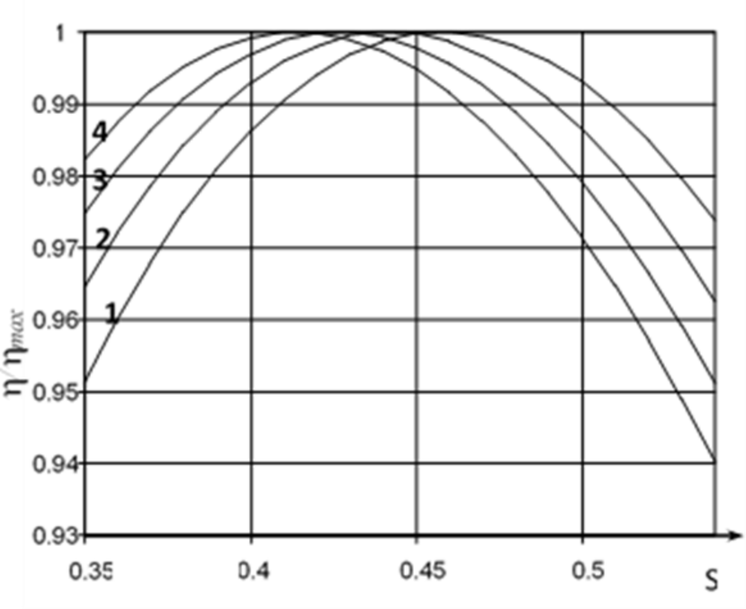


Fig.3.4 Dependence $\eta/\eta_{\max}$ from sliding at T = 300 K: 1. - zT = 0.4, 2. - zT = 0.6, 3. - zT = 0.8, 4. - –zT = 1.0.

As can be seen from (3.44), the inequality $S_0 < 1/2$ is always satisfied. The inequality increases with increasing parameter zT. This means that the maximum power mode and the maximum efficiency mode will never coincide. As can be seen from Fig. 3.4, for modern thermoelectric materials, for which $zT \leq 1$ correlation $\eta_p/\eta_{max} \geq 0.97$. Therefore, the efficiency in the mode of maximum power and maximum efficiency differs slightly.

\

3.5 Magnetic converter system

A magnetic system is a magnetic circuit that consists of two parts: a permanent magnet with a steel magnetic circuit and an air gap. In a magnetic circuit, the magnetic field strength Hc can be considered the same at all points of the midline [24]. In the air gap, the magnetic field strength is associated with the magnetic induction ratio

$$H_n = \frac{B_n}{\mu_0}, \tag{3.40}$$

The magnetic system of TEMC is schematically shown in Fig.3.5.

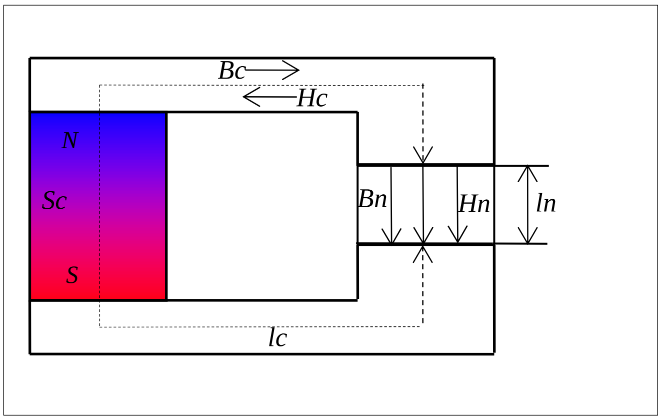


Fig.3.5 Scheme of the TEMK magnetic circuit with air gap

With a small length of the air gap, the scattering of the magnetic flux can be neglected. Taking the cross section of the air gap Sn equal to the cross section of the magnetic circuit Sc, we find the induction at all points of the magnetic circuit

$$B_c = \frac{\Phi}{S_c} = \frac{\Phi}{S_n} = B_n, \tag{3.41}$$

Choosing the integration circuit along the midline in the direction of magnetic induction $B_c = B_n$ we write the law of total current in integral form. Since there is no magnetizing current in the circuit, then

$$\oint \vec{H} d\vec{l} = H_c l_c + H_n l_n = 0, \tag{3.42}$$

where

$$H_c = -H_n \frac{l_n}{l_c} = -\frac{B_c}{\mu_0}\frac{l_n}{l_c} = -N_B \frac{B_c}{\mu_0}, \tag{3.43}$$

where $N_B = l_n / l_c$ - degaussing coefficient by induction.

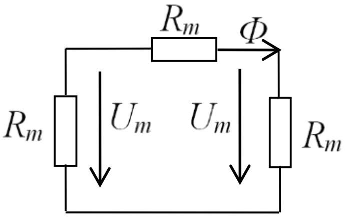


Fig. 3.6 Scheme of the magnetic circuit TEMK

Thus, despite the absence of magnetizing currents, the magnetic field strength at all points of the magnetic circuit is nonzero. In the air gap, the direction of the magnetic field vector coincides with the direction of the magnetic induction vector, and inside the magnetic circuit they are directed in the opposite direction (Fig. 3.5). Since the negative value of the magnetic field strength Hc corresponds to the positive values of the magnetic induction $B_c = B_n$, the magnetic state of the magnetic circuit is determined by the equation of the magnetic state

$$B_c = -\frac{B_r}{H_{cb}} H_c + B_r, \tag{3.44}$$

where B_r is the residual magnetization, H_c is the coercive force of the permanent magnet.

Solving the system of equations (3.53) and (3.54) with respect to magnetic induction we obtain:

$$B_c = B_n = \frac{B_r}{1 - \frac{B_r}{\mu_0 H_{cb}} N_B}, \tag{3.45}$$

To excite the magnetic flux in the TEMC, we use a permanent magnet made of ALNICO-5DG alloy with residual induction B_r = 1.30T and coercive force H_{cb} = -56000 A/m. Put the lengths l_c = *125mm*, and l_n = 10mm and find the value of magnetic induction $B_c = B_n$ = 0.53T. The value of the coercive force is H_{cb} = -33530 A/m. Find the magnetic flux through the cross section of the rotor of the converter

$$\Phi = B_c \cdot \pi \cdot r^2 = 0.53 \cdot 3.14 \cdot (0.1)^2 = 17 \cdot 10^{-3} Вб$$

Parameters of permanent magnets. Table 3.1

Grade	Equivalent MMPA Class	Br		Hcb		BH(max)		WT	Remark
		mT	Gs	kA/m	Oe	kJ/m³	MGOe	°C	
LN10	ALNICO3	600	6000	40	500	10	1.2	450	Isotropic
LN13	ALNICO2	700	7000	48	600	12.8	1.6	450	
LNGT18	ALNICO8	580	5800	100	1250	18	2.2	550	
LNG37	ALNICO5	1200	12000	48	600	37	4.65	525	
LNG40		1250	12500	48	600	40	5		
LNG44		1250	12500	52	650	44	5.5		
LNG52	ALNICO5DG	1300	13000	56	700	52	6.5		
LNG60	ALNICO5-7	1350	13500	59	740	60	7.5		

3.6 Cooling systemconverter

In the development of heat engines, which includes the converter, an important task is to choose a cooling system. Cooling systems are divided into passive and active. Passive cooling systems are the simplest and most common way of thermal stabilization of various equipment.

The heat supplied from the heater to the converter is conductively transferred to the hot collector of the converter, and then convectively transferred to the refrigerator in the role of which is the environment. This method of cooling is characterized by relatively low efficiency. Convection can be increased if a massive radiator is connected to the converter. This will dramatically increase the surface area of heat exchange with the environment.It is obvious that nthe surface of the radiator scattering surface must be large enough. For a rough estimate, it is considered that for 1 W of dissipated heat you need to take a radiator with a scattering area of 30 - 60 cm^2.

3.7 Calculation of TEMC parameters

Let's estimate parameters of the converter which works in the mode of the maximum power. Assume that the branches of the device are made of thermoelectric material based on the alloy Bi-Te-Sb-Se with a total area of $S = 300 cm^2$ height $h = 0.4 cm$. Let the radius of the rotor $r = 5$ cm, and the magnetic induction $B = 0.53T$. Power, electromagnetic torque, rotor speed and current at maximum power at an average temperature $T = 300K$ are given in table. 3.3.

Naturally, with increasing geometric dimensions of the converter and the use of more advanced thermoelectric and electrical materials, its power and efficiency will increase. Since all heat engines operating at the same heater and refrigerator temperatures have the same thermodynamic conditions, the value of efficiency should not be the only criterion when comparing them.

The thermoelectric converter can be used in places where energy needs cannot be met by conventional sources, as well as in places where emergency redundancy is required. The miniature converter can be used to create autonomous heat meters [21].

3.8 Operating modes

As a result of thermodynamic reversibility of thermoelectric effects, the converter can operate in three main modes: motor (motor mode), thermal heating (heat pump mode) and thermal cooling (thermoelectric refrigerator mode). The diagrams showing these modes are shown in the figure.

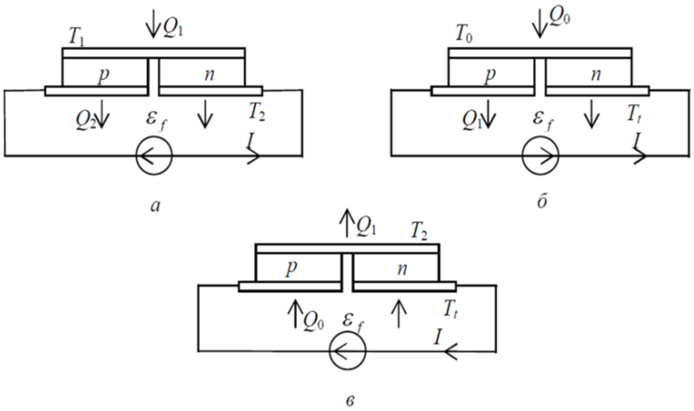


Fig.3.7 Modes of operation of the converter. a - motor, b - heat-heated, c - heat-cooling.

In motor mode ($0 \leq S \leq 1$), the converter converts the thermal energy coming from the heater into mechanical work.

Reducing the electromagnetic torque of the rotor to zero corresponds to the mode of idle (idling). If you continue to rotate the rotor of the converter in the same direction, but with a frequency of n> nmax ($-\infty < S < 0$), then with the combined action of the electromagnetic induction effect and the Peltier effect, thermal energy from the environment will be pumped to the collector of the converter. The collector plate will be heated by the release of Peltier heat. In addition to the Peltier heat, the Joule heat will also be released in the collector plate. Therefore, the thermal efficiency of such a heater will be higher than heating only with Joule heat. The converter will operate in thermoheating mode (heat pump mode) (Fig. 3.7 b).

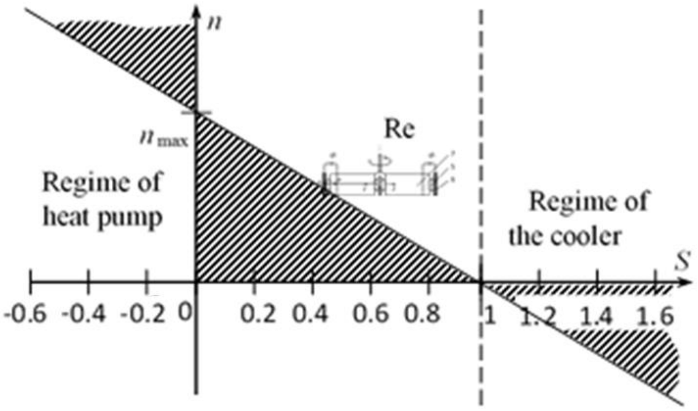


Fig. 3.8 Dependence of the rotor speed of the converter on sliding

If a sufficiently large braking torque is applied to the rotor of the converter, the rotor will stop. At the further untwisting of a rotor in the direction of the braking moment ($1 < S < \infty$) the direction of current in the electrical circuit will change to the opposite. As a result, the converter collector will absorb heat energy from the environment. The converter will go into cooling mode (Fig. 3.7c).

4 LIFE SAFETY AND FUNDAMENTALS OF LABOR PROTECTION

4.1 Analysis of possible hazardous and harmful production factors, electrical safety and fire hazard

Danger can lie in wait for us in the form of various negative factors almost everywhere [44-49]. Even in the most harmless workplaces, we can talk about the harmful effects of computers, prolonged sedentary work and much more. In many industries, work is associated with the constant impact on workers of adverse conditions. Harmful and hazardous factors of production (VF) are inextricably linked. VF are factors which as a result of the long or short-term influence on the person lead to deterioration of a state of health or to an injury. In industries with such working conditions, various accidents occur quite often.

VF are factors that, acting on the employee, reduce his ability to work or lead to various diseases, they are often called occupational diseases. It should be noted that the boundary between these two groups of factors is quite conditional. Under certain conditions, harmful production factors can become dangerous. For example, high humidity refers to adverse working conditions, it can cause various diseases of the respiratory system. If a person has to work with electricity in such conditions, it becomes too dangerous, not just harmful.

All factors in any company may have different origins. You can often encounter unfavorable working conditions that arise through the fault of management. This issue needs special attention from regulatory authorities. It should be noted that there is no clear line between harmful and dangerous factors, it is always conditional and can be destroyed at any time. There are always technological processes and equipment in production, which are the source of HF emissions. These proceedings include: cleaning parts with chemicals; painting of equipment; welding works; processes of application of protective anticorrosive coatings; processing or recycling of metals. In the implementation of all these processes, the release of harmful substances is inevitable, but, as a rule, their increased formation is associated with non-compliance with technologies or incompetent use.

In many industries it is simply impossible to avoid the influence of some factors. Among them a special place is occupied by: temperature, high humidity and radiation; electromagnetic fields; laser and ultrasonic radiation; vibration; loud noise; lighting, which can be both too intense and insufficient, which is equally harmful to eyesight; exposure to dust and aerosols; working parts of the equipment. Each factor alone does not seem to pose a particular danger to human health in the short term. But often the employee is in their environment for a long time, and several more, so their influence becomes quite noticeable.

At the enterprises where in shops there are machines and other equipment, without noise, as a rule, does not manage. Constantly working technique makes loud sounds that can change their intensity. If a person is forced to regularly experience such exposure, it will negatively affect his health. From a loud noise the head starts to ache, pressure increases, hearing acuity decreases. Eventually, such conditions reduce efficiency, fatigue, reduced attention, and this can lead to an accident. Managers in such enterprises should take care of their employees to try to reduce the negative impact of noise on the body.

As a result of the constant influence of this factor begins to suffer not only the nervous system, but also the musculoskeletal and analyzer systems. Workers who are forced to work in such conditions often complain of headaches, dizziness, dizziness.

If you add the influence of concomitant factors such as humidity, heat, noise, it only exacerbates the harmful effects of vibration. If the use of protective equipment is established quite effectively in harmful enterprises, workers will be exposed to hazardous substances to a much lesser extent.

Psychophysiological factors include the burden of working conditions and its intensity. The stress of work means the load on the nervous system and sensory organs. These include long-term mental work, monotony of processes, emotional overload. All these are harmful production factors, which, if we understand, almost every one of us in his workplace feels to one degree or another.

At any enterprise it is necessary to try to provide a comfortable environment in order to create favorable conditions for employees. This applies, first of all, to the purity of the air in the production premises. Sanitary and hygienic services divide the main harmful production factors into chemicals and industrial dust.

The negative impact of dust is manifested in the fact that it can provoke the development of lung disease. At any enterprise, employees are affected by harmful factors of production from several groups, ie complex.

Despite all measures aimed at neutralizing the harmful effects of factors, it is impossible to achieve ideal working conditions. This does not allow to make the features of technological processes, products and raw materials for its manufacture. Therefore, for managers, protection against harmful production factors is a priority.

It often happens that all the measures taken can not ensure completely safe working conditions, in these cases, without the use of PPE simply can not do. It can be concluded that personal protective equipment, on the one hand, reduces the impact of harmful factors, and on the other - may pose another danger to the health of the employee. Safety measures are aimed primarily at ensuring that harmful factors of production do not have a dangerous effect on humans. To this end, safety training must be carried out at any enterprise. The date and content are recorded in a special journal signed by all instructed and the person who conducted this instruction.

4.2 Protection of personnel and the environment from hazardous production factors

The action of the electromagnetic pulse of lightning on metal elements of building structures, electrical and electronic systems is a secondary action of lightning. Secondary actions of lightning are associated with the action on the object of the electromagnetic field of close discharges. This field has two components: electrostatic and electromagnetic induction.

Electrostatic induction is caused by the movement of charges in the lightning channel. Electrostatic induction effect is manifested in the form of pulse overvoltages that occur on the metal structures of the object. The magnitude of the surge voltage depends on the magnitude of the lightning current, the distance to the point of impact, the ground resistance. In the absence of proper grounding, the surge voltage can reach hundreds of kilovolts and create the risk of electric shock and sparks between parts of the object.

Electromagnetic induction is due to changes in lightning current over time. Electromagnetic induction leads to the formation in the metal circuits of the EMF object, proportional to the rate of change of lightning current and the area covered by the circuit. Long communications in modern industrial buildings can form circuits covering a large area, in which there is a risk of EMF in the tens of kilovolts. In places of convergence of long metal structures, in the gaps of open circuits there is a danger of overlapping and sparks with possible energy dissipation of about tenths of a joule.

According to GOST 12.1.004 the fire danger of secondary actions of lightning consists in the spark discharges arising as a result of induction and electromagnetic influence of atmospheric electricity on the production equipment, pipelines and building designs. A spark energy exceeding 250 mJ is sufficient to ignite combustible substances with a minimum ignition energy of up to 0.25 J.

It is also dangerous to bring high potential into the house on metal communications, not only when hit directly by lightning, but also when the location of communications in the immediate vicinity of the lightning rod. If the safe distances between lightning rods and communications are not observed, the energy of possible spark discharges reaches values of 100 J and more, ie it is sufficient to ignite all combustible substances.

Protection against electrostatic induction is carried out by connecting equipment to the ground for the removal of electrostatic charges induced by lightning in the ground. Protection against electromagnetic induction is to establish by welding jumpers between long metal structures in places of their convergence less than10 cm. The interval between the jumpers should not exceed 20 m. This allows the induced lightning current to pass from one circuit to another without the formation of electrical discharges. Protection against the introduction of high potentials in the building is carried out by connecting to the grounding of metal structures before their introduction into the building.

For the device of artificial grounding devices steel vertically laid in the earth pipes with a diameter from 3 to5 cmand wall thickness not less than3.5 mm, 2.5 ... 3 m long; metal rods with a diameter of 10-12 mm, up to10 m; angular steel 40Ch40Ch4, length 2.5-5 m. It is forbidden to use aluminum sheaths of power cables and uninsulated aluminum conductors for artificial earthing devices.

Thus, in compliance with the requirements set out in the PUE-7, regarding the arrangement of protection against EMI lightning, will be preserved lighting equipment and its components, as well as the lives of workers who service this equipment.

GENERAL CONCLUSIONS

1. A promising area of energy-saving technologies can be a new device semiconductor thermoelectromechanical thermal energy converter (TEMC), in which the processes of generation, transmission and consumption of thermoelectric current are integrated in one deviceTEMC is designed to convert low-potential thermal energy (several tens of degrees) into mechanical (motor mode).

2. It is shown that it is possible to operate the TEMC in thermosetting and thermally oxidizing modes.

3. The main parameters of TEMC are set: power, electromagnetic moment, frequency of revolutions, efficiency and their optimization in the modes of maximum power and maximum efficiency is carried out.

4. It is shown that the power of TEMC is directly proportional to the square of the temperature difference between the heater and the refrigerator and will increase with increasing linear dimensions of the device, improving material characteristics and reducing unproductive losses of electricity and heatTEMC is a low-speed device. The rotor speed is only n = 20-60 1/m.

5. Since the electromagnetic moment of TEMC is in direct dependence on the magnetic flux, and the frequency of rotation of the flood is in the inversion, the magnitude of the magnitude is greater.

6. The use of the proposed scheme of magnetic flux excitation will maintain a stable operation of the TEMC in a wide range of temperatures.

7. To thermostabilize the operating temperature of the "cold" collector TEMK can be used a system of heat pipes connected to a passive radiator of a large area.

8. The efficiency of TEMC is a few percent due to the fact that its work is subject to thermodynamic limitations of the Carnot cycle. However, such restrictions are common to all heat engines that operate with a small temperature difference between the heater and the refrigerator, and should not be the only criterion in assessing their performance.

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