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ON THE EFFECT OF INTERMETALLICS ON THE ELECTRICAL AND THERMAL CONTACT RESISTANCES THERMOELECTRIC MATERIAL - METAL

It is shown that the electrical and thermal contact resistances thermoelectric material (TEM) - metal in structures with anti-diffusion layers increase significantly, if transient contact layer consists of a sublayer of intermetallic and a sublayer of TEM-intermetallic composite. In a couple of bismuth telluride-nickel, $NiTe_2$ is a dominant intermetallic. With a total thickness of transient layer of bismuth telluride-nickel ditelluride of 40 μm its electrical resistance will vary in the range from $1.28\cdot10^{-6}$ to $3.46\cdot10^{-6}$ $Ohm\cdot cm^2$, and thermal –in the range from 0.131 to 0.195 $K\cdot cm^2/W$. Over time, this layer can grow and, for instance, with a total thickness of 200 μm its electrical contact resistance will vary in the same temperature range from $6.40\cdot10^{-6}$ to $1.73\cdot10^{-5}$ $Ohm\cdot cm^2$, and thermal – in the range from 0.655 to 0.975 $K\cdot cm^2/W$. This growth significantly affects not only the consumer characteristics, but also the reliability, life and durability of thermoelectric energy converters. In addition, it is shown that nickel ditelluride - bismuth telluride composite is not a highly efficient thermoelectric material, but the dimensionless thermoelectric figure of merit of the bismuth telluride - high-conductivity metal clusters can become significantly higher. The boundary thermoelectric figure of merit of such a composite was found. Bibl. 9, Fig. 5.

Key words: contact resistance**,** nonstationary diffusion, intermetallic, thermoelectric material, doping, metallized composite, percolation threshold, nanoclusters, optimal composition of composite, boundary dimensionless thermoelectric figure of merit, high-temperature superconductivity.

Introduction

It is known that the electrical and thermal contact resistances TEM - metal have a significant impact on the consumer properties of thermoelectric energy converters, especially under conditions of miniaturization. But if contact structures, and, consequently, transient contact layers, are created by soldering, the possibility of lowering these resistances is significantly limited by the formation of intermetallics, which have significantly lower electrical conductivity and thermal conductivity than "pure" metals. It should be noted that nickel itself diffuses into bismuth telluride and alloys based on it relatively slowly [1]. On the other hand, during the manufacture and aging of contact structures, tellurium intensively diffuses into nickel, forming due to thermally activated reactions at the interface, layers of nickel telluride, among which nickel ditelluride $NiTe_2$ dominates [2]. The thermoelectric properties of nickel ditelluride formed in this way have not been studied. However, the thermoelectric properties of specially prepared alloys of the *Ni-Te* system of various compositions were studied

[3, 4]. Therefore, in [3], in particular, it is noted that *$NiTe_2$* at 300 K has an electrical conductivity of 7500 S/cm and a thermoEMF of about 10 µV/K. Thus, to a certain extent, its properties are similar to those of a metal.

It is the formation of this intermetallic that primarily causes a significant increase in the electrical and thermal contact resistances of transient contact layers. Moreover, intermetallic layers are able to grow under the influence of temperature, and, consequently, electric current. This leads to an increase in the electrical and thermal contact resistances. In addition, intermetallics formed as a result of interfacial reactions have significantly lower mechanical strength than alloys of the same composition. Thus, the formation of intermetallics has a negative effect not only on consumer characteristics, but also on the reliability, life and durability of thermoelectric energy converters. However, the purpose of this paper is mainly to study the temperature dependences of the electrical and thermal contact resistances of transient layers formed by intermetallics.

Calculation of contact layer structure

The distribution of intermetallic molecular clusters in TEM will be found from the equation of nonstationary diffusion which in the case of zero intensity of the source is given by:

$$\frac{\partial n}{\partial t} - D\frac{\partial^2 n}{\partial x^2} = 0, \tag{1}$$

where $n-$concentration of intermetallic clusters at depth x from TEM-metal interface, $t-$time, $D-$diffusion coefficient which we consider independent of the coordinate, time and concentration of intermetallic clusters. For the unambiguous solution of Eq. (1) we make the following model assumptions: 1) at the beginning of the process, a thin layer of cluster atoms of thickness δ with concentration n_0 is created; 2) near the interface, concentration n_0 is maintained all the time. Under assumption 1, Eq.(1) has the following solution:

$$n(x,t) = n_0\left[\operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right) - \operatorname{erf}\left(\frac{x-\delta}{2\sqrt{Dt}}\right)\right], \tag{2}$$

where $\operatorname{erf}(...)-$the so-called error integral.

But in order for assumption 2 to be satisfied, a layer of thickness δ must change with time according to the law $\delta = 6\sqrt{Dt}$. It is this change that actually happens in many cases. In this case, this is a layer of intermetallic. It follows from formula (2) that the actual contact structure consists of two parts: a layer of intermetallic of thickness $6\sqrt{Dt}$ and a layer of TEM of thickness $6\sqrt{Dt}$ with interspersed clusters of intermetallic, the concentration of which decreases to zero. This coordinate distribution in the structure of total thickness $12\sqrt{Dt}$ is schematically shown in Fig.1.

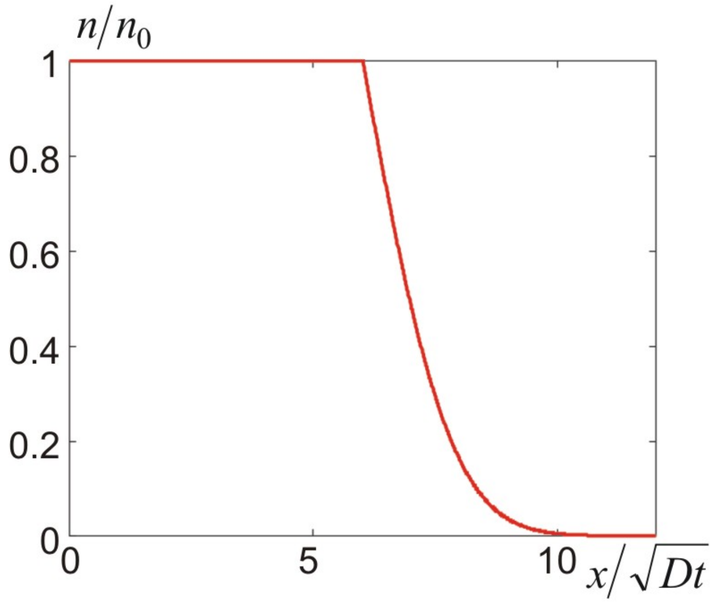

Fig.1.Distribution of intermetallic clusters in transient layer

This distribution is matched by distribution of the volumetric fraction of intermetallic in transient layer normalized to transient layer thickness:

$$\nu_i(y)=\frac{(A_i/\gamma_i)[1-\mathrm{erf}(3y)]}{(A_i/\gamma_i)[1-\mathrm{erf}(3y)]+(A_s/\gamma_s)\mathrm{erf}(3y)}, \tag{3}$$

where A_i, A_s, γ_i, γ_s – molecular masses and densities of intermetallic and TEM, respectively, $\mathrm{erf}(z)$ – the so-called error integral. Assuming by convention a cluster of intermetallic to be spherical, we define its minimum diameter. It is equal to:

$$d_{\min}=\sqrt[3]{\frac{6A_iN_{\min}}{\pi\gamma_iN_A}}, \tag{4}$$

where N_A – Avogadro's number, $N_{\min}$ – the minimum number of atoms in a cluster required to attribute to it the macroscopic properties of intermetallic as a whole. If a cluster comprises, for instance, 10^6 atoms, then such macroscopic properties can be attributed to it with an accuracy of 0.1%. Assuming $A_i=312$, $\gamma_i=7750\,\mathrm{kg/m^3}$, we obtain $d_{\min}=50.3\,\mathrm{nm}$. Hereinafter, we will assume that the clusters have a diameter of 100 nm.

Calculation of the electrical and thermal contact resistances and discussion of the results

Taking into account that in the context of the above approach a transient layer is considered as a composite where the percolation effect occurs, its electrical conductivity σ_c and thermal conductivity κ_c will be determined as [5, 6]:

$$\sigma_c = 0.25\left\{\sigma_s(2-3\nu_i)+\sigma_i(3\nu_m-1)+\sqrt{[\sigma_s(2-3\nu_i)+\sigma_i(3\nu_i-1)]^2+8\sigma_i\sigma_s}\right\}, \tag{5}$$

$$\kappa_c = 0.25\left\{\kappa_i(2-3\nu_i)+\kappa_i(3\nu_i-1)+\sqrt{[\kappa_s(2-3\nu_i)+\kappa_i(3\nu_i-1)]^2+8\kappa_i\kappa_s}\right\}. \tag{6}$$

The thermoEMF of transient contact layer will be determined as:

$$\alpha_c = \frac{\int_0^1 \{(\alpha_i/\kappa_i)\nu_i(y)+(\alpha_s/\kappa_s)[1-\nu_i(y)]\}dy}{\int_0^1 \{\kappa_i^{-1}\nu_i(y)+\kappa_s^{-1}[1-\nu_i(y)]\}dy} \ . \tag{7}$$

The electrical and thermal contact resistances will be determined for the formulae:

$$r_{ce} = d\int_0^1 \frac{dy}{\sigma_c}, \tag{8}$$

$$r_{te} = d\int_0^1 \frac{dy}{\kappa_c}. \tag{9}$$

In addition, to these values we add the electrical and thermal contact resistances of intermetallic layers proper.

Approximation of the necessary temperature dependences of the kinetic coefficients of TEM and intermetallic on the basis of known general relations [7,8] according to the model assumptions presented in [6,9] will be carried out in the following order.

According to known thermoEMF value α_{s0} of TEM at a certain temperature T_0 from equation:

$$\alpha_{s0} = \frac{k}{e}\left[\frac{2F_1(\eta_0)}{F_0(\eta_0)}-\eta_0\right] \tag{10}$$

we determine the value η_0 of reduced chemical potential of carrier gas at this temperature.

Using the condition of constant charge carrier concentration, from the equation

$$\frac{T^{1.5}F_{0.5}(\eta)}{T_0^{1.5}F_{0.5}(\eta_0)} = 1 \tag{11}$$

we determine the temperature dependence of reduced chemical potential η in given temperature range.

From the relation

$$L_s(\eta) = \left(\frac{k}{e}\right)^2\left[\frac{3F_2(\eta)}{F_0(\eta)}-\frac{4F_1^2(\eta)}{F_0^2(\eta)}\right] \tag{12}$$

we determine the temperature dependence of TEM Lorentz number.

The temperature dependence of TEM electrical conductivity is determined as

$$\sigma_s = \sigma_{s0}\left(\frac{T_0}{T}\right)^{1.5}\frac{F_0(\eta)F_{0.5}(\eta_0)}{F_{0.5}(\eta)F_0(\eta_0)}\,. \tag{13}$$

The temperature dependence of thermal conductivity is determined as:

$$\kappa_s = \sigma_s L_s(\eta)T + \left[\kappa_{s0} - \sigma_{s0}L_s(\eta_0)T_0\right]\frac{T_0}{T}\,. \tag{14}$$

In formulae (8) – (11), $F_m(\eta)$ denote the Fermi integrals that are determined by the following relation:

$$F_m(\eta) = \int_0^\infty x^m\left[\exp(x-\eta)+1\right]^{-1}dx\,. \tag{15}$$

In conformity with [3], the *NiTe₂* intermetallic will be considered as metal, and its electrical conductivity will be assumed to be inversely proportional to temperature:

$$\sigma_i = \sigma_{i0}(T_0/T), \tag{16}$$

and its thermal conductivity, in accordance with the Wiedemann-Franz law, will be considered mainly due to free charge carriers, independent of temperature and equal to:

$$\kappa_i = \left(\pi^2k^2/3e^2\right)\sigma_{i0}T_0\,. \tag{17}$$

Moreover, taking into account the scattering of charge carriers in the intermetallic at the cluster boundaries, the values of electrical and thermal conductivity of the intermetallic "bulk sample" will be multiplied by the following correction factor:

$$K_c = 1.5\int_0^1\int_{-1}^1 \frac{(d_cT/l_0T_0)\sqrt{1+x^2-2xy}}{(d_cT/l_0T_0)\sqrt{1+x^2-2xy}+2}x^2dydx\,. \tag{18}$$

In this formula, d_c – cluster diameter, l_0 – mean free path of electron in the intermetallic at a temperature of T_0.

Note that we use this correction factor exclusively for transient layer with clusters. We consider the intermetallic layer to be solid, and, therefore, for it we assume the correction factor equal to 1.

Results of calculations of the temperature dependences of the electrical and thermal resistances of bismuth telluride-nickel in the presence of intermetallics in transient layer are given in Figs. 2 and 3.

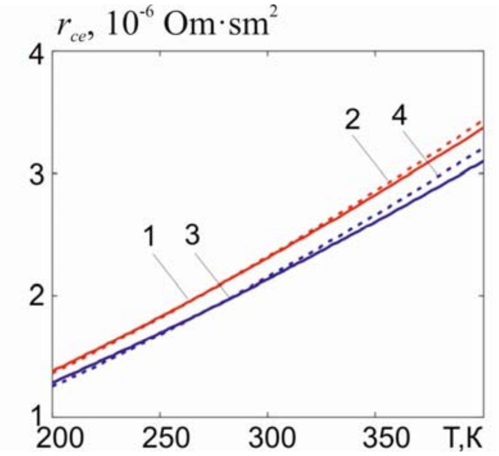

Fig.2. Temperature dependences of electrical contact resistance of transient contact layer 40 μm thick: 1,2 – prior to levelling the concentration of intermetallic clusters excluding and taking into account charge carrier scattering at the boundaries of clusters, 3,4 – after levelling the concentration of intermetallic clusters excluding and taking into account charge carrier scattering at the boundaries of clusters

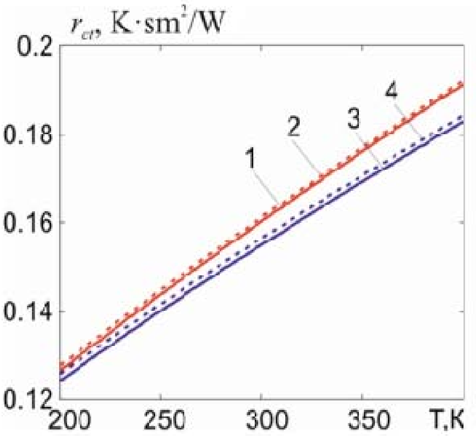

Fig.2. Temperature dependences of thermal contact resistance of transient contact layer 40 μm thick: 1,2 – prior to levelling the concentration of intermetallic clusters excluding and taking into account charge carrier scattering at the boundaries of clusters, 3,4 – after levelling the concentration of intermetallic clusters excluding and taking into account charge carrier scattering at the boundaries of clusters

When plotting, it was assumed that T_0=300 K, α_{s0}=200 μV/K, σ_{s0}=800 S/cm, κ_{s0}=1.4 W/(m·K), σ_{i0}=7500 S/cm, l_0=5 nm.

The plots show that for the total thickness of bismuth telluride - nickel ditelluride transient layer of 40 μm its electrical contact resistance will vary in the range from $1.28 \cdot 10^{-6}$ to $3.46 \cdot 10^{-6}$ Ohm·cm^2, and thermal - in the range from 0.131 to 0.195 K · cm^2 / W. Over time, this layer can grow, and, for example, with a total thickness of 200 μm, its electrical contact resistance will vary in the same temperature range from $6.40 \cdot 10^{-6}$ to $1.73 \cdot 10^{-5}$ Ohm·cm^2, and thermal - in the range from 0.655 to 0.975 K·cm^2/W. This growth has a significant impact not only on consumer characteristics, but also on the reliability, life and durability of thermoelectric energy converters. Note also that after levelling the concentration of clusters in transient layer, the electrical and thermal contact resistances somewhat decrease in comparison with the non-uniform distribution, which is dictated by the processes of nonstationary diffusion; therefore, this levelling can be considered to be a positive factor. The scattering of charge carriers at the boundaries of clusters as a whole increases the electrical and thermal contact resistances, although only slightly.

During the calculations, we had to assume that the intermetallic in the contact layer has the same properties as the alloy of the corresponding composition. But this is a very significant approximation, because the conditions of formation of this intermetallic due to interfacial reactions in the contact layer are radically different from the conditions that occur during the direct fusion of nickel with tellurium. This difference can only lead to an increase in the electrical and thermal contact resistances compared to their calculated values.

Can nickel ditelluride-bismuth telluride composites serve as thermoelectric materials?

To answer this question, the dependence of the dimensionless thermoelectric figure of merit of the aforementioned composites at a temperature of 400 K on the volumetric content of nickel ditelluride in them was calculated, which is shown in Fig. 4.

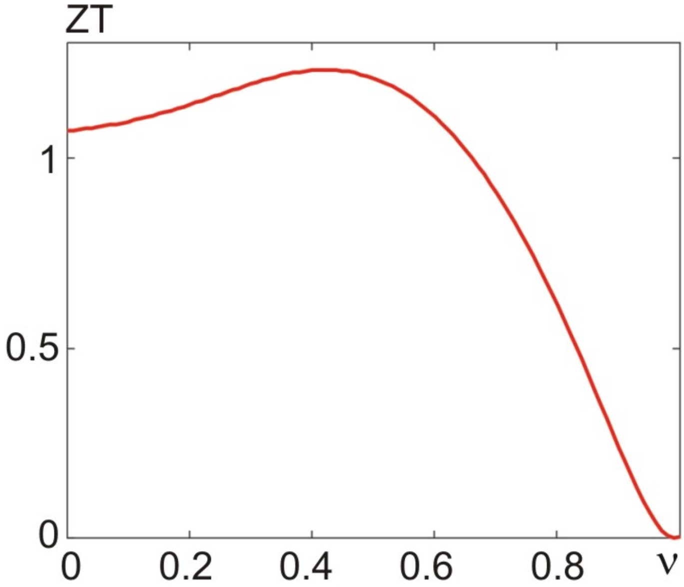

Fig.4. Dependence of the dimensionless thermoelectric figure of merit of nickel ditelluride-bismuth telluride composites at a temperature of 400 K on the volumetric content of nickel ditelluride in them

When plotting, it was assumed that the thermoEMF of nickel ditelluride is equal to 10 μV/K and does not depend on temperature. The plot shows that when the content of nickel ditelluride is approximately 50 vol.%, the thermoelectric figure of merit increases by approximately 20% compared to pure bismuth telluride. Then it rapidly decreases to the small value inherent in pure nickel ditelluride. But this is true only when our hypothetical material is really a composite and the nickel ditelluride in it has the properties of an alloy of appropriate composition. Only in this case, you can consider the feasibility of manufacturing and using such material, also taking into account the other aspects mentioned above.

On the boundary opportunities of “metallized” thermoelectric composites

Note that even at first glance a slight increase in thermoelectric figure of merit of the above hypothetical composite compared to pure TEM, shown in Fig.4, is possible mainly because the addition of highly conductive, and hence highly thermally conductive, impurity to the original TEM at a fairly large interval of the volumetric content of the impurity has relatively little effect on the thermoEMF of the composite as a whole. Therefore, assuming that the thermoEMF of an impurity is small or even equal to zero in absolute value, it makes some sense to investigate the effect of this impurity on the thermoelectric figure of merit of the composite with increasing electrical conductivity. The results of this study are shown in Fig. 5.

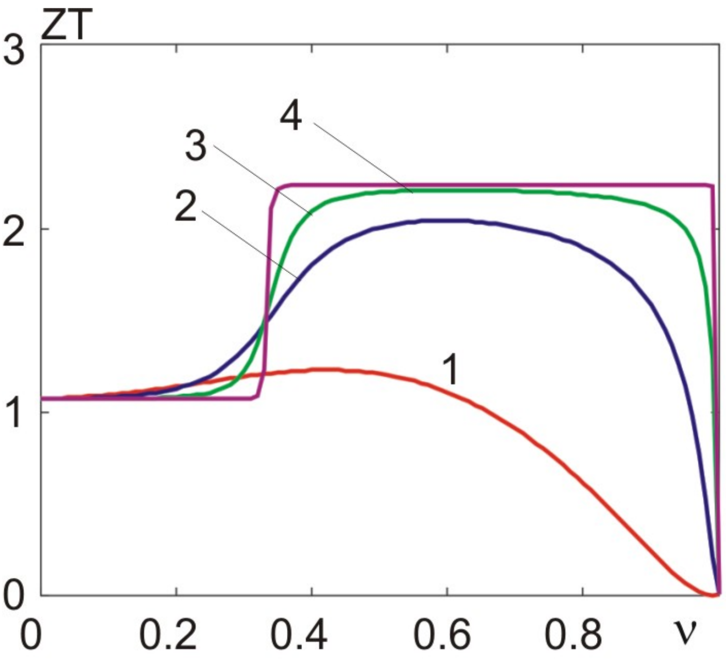

Fig.5. Dependence of thermoelectric figure of merit of metal impurity-bismuth telluride composites on the volumetric fraction of impurity at a temperature of 400 K and the value of impurity electric conductivity at 300 K in S/cm: 1 – 7500, 2 – 75000, 3 – $5\cdot 10^5$, 4 – $5\cdot 10^7$.

From the plots we see that with an increase in the electrical conductivity of a metal impurity, firstly, the percolation threshold becomes sharply expressed, and secondly, the maximum thermoelectric figure of merit of the “metallized” composite rather quickly tends to the maximum attainable value. Obviously, the boundary value of thermoelectric figure of merit of a "metallized" thermoelectric composite at a certain temperature T is equal to:

$$ZT_{\max} = \frac{\alpha_s^2(T)\sigma_m T}{\left(\pi^2/3\right)\left(k/e\right)^2 \sigma_m T} = \frac{3e^2\alpha_s^2(T)}{(\pi k)^2}. \qquad (19)$$

It is important that this formula includes the thermoEMF of *semiconductor* TEM at a given temperature, but the electrical conductivity, thermal conductivity, hence the Lorentz number, of *metal*. It is clear that this approach correctly reflects physical situation if and only if the semiconductor and metal, when incorporated into the composite, whatever its composition, retain their inherent macroscopic values of the kinetic coefficients, including their temperature dependences.

Then, substituting, for instance, $\alpha_s(400) = 235$ μV / K, we obtain $ZT_{max} = 2.236$, which more than twice exceeds the thermoelectric figure of merit typical of traditional alloys based on *Bi(Sb) – Te(Se)* system. An even more striking result can be obtained by taking as TEM, for example, zinc antimonide, for which the thermoEMF can be considered equal to, say, 700 μV / K.

Then the maximum value of thermoelectric figure of merit of a "metallized" thermoelectric composite based on it is 19.8, while, as usual, alloys of the Zn-Cd-Sb system have more than 1 - 2 orders of magnitude lower thermoelectric figure of merit. Thus, the question arises about the technological feasibility of manufacturing such *metallized composites*, rather than just *alloyed with metal impurities materials*, which, unlike composites, obviously will not have such advantages, their stability, durability and the possibility of being used for creation of thermoelectric energy converters taking into account the specificity of their operation.

It should be noted that the reactions between metal and TEM components with the formation of intermetallics with relatively high electrical resistivity are a significant obstacle to significantly increase the thermoelectric figure of merit and efficiency of TEM both by doping them with metal impurities and by creating "metallized" thermoelectric composites. Based on the results of the study, we can formulate the following list of requirements for materials suitable for obtaining highly efficient "metallized" two-phase thermoelectric composites:

1) the semiconductor TEM must have the highest possible absolute value of thermoEMF in the operating temperature range;

2) the metal must have the lowest possible electrical resistivity and either not react with the components of the TEM, or form with them intermetallics, the electrical conductivity and thermal conductivity of which would differ as significantly as possible from the electrical and thermal conductivity of the TEM upward;

3) the thermoEMF of a metal or intermetallic under these conditions is not critical can be small in the absolute value.

However, even if these requirements are compatible with each other and technologically feasible, the composite must still have such thermal and mechanical properties and such compatibility with other materials that would allow it to be used to create specific devices.

In connection with all of the above, the reader may ask what will happen if, instead of metal impurities, specially made granules based on high-temperature superconducting ceramics are used. At this stage, the author is not ready to give a well-argued answer to such a question. There are two reasons for this. The first is that superconductivity, for example, at room temperature has not yet been achieved. The second reason is that the traditional concepts of thermoelectric figure of merit and efficiency of TEM, no matter how “good” or “bad” it is, have a certain meaning, not least because the charge transfer in it is described by Ohm's law. And in the superconducting state, Ohm's law is applicable only to the "normal", that is, not the superconducting part of the material. The electrodynamics of the superconducting part is fundamentally different. And, as can be seen from Fig. 5, there is no urgent need for unlimited electrical conductivity of the "metal" part of the composite. On the other hand, superconducting ceramics, as a component of TEM, may be useful in creating high-quality cooling materials and devices, especially miniature ones, for cryogenic temperatures, but this issue requires special thorough research, which is not the subject of this paper.

Conclusions

1. It is shown that the formation of intermetallics in the TEM-metal transient contact layer significantly increases the corresponding thermal and electrical contact resistances.
2. Conditions of high figure of merit for two-phase "metallized" thermoelectric composites are established and requirements to materials from which it is expedient to make them are formulated.
3. In general, the boundary value of the thermoelectric figure of merit is found for “metallized” thermoelectric composites.

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ПРО ВПЛИВ ІНТЕРМЕТАЛІДІВ НА ЕЛЕКТРИЧНИЙ ТА ТЕПЛОВИЙ КОНТАКТНІ ОПОРИ ТЕРМОЕЛЕКТРИЧНИЙ МАТЕРІАЛ – МЕТАЛ

Показано, що електричний та тепловий контактні опори термоелектричний матеріал (ТЕМ) метал у структурах з антидифузійними шарами істотно зростають, якщо перехідний контактний шар складається з підшару інтерметаліду та підшару композиту ТЕМ – інтерметалід. У парі телурид вісмуту – нікель таким домінантним інтерметалідам є $NiTe_2$*. За загальної товщини перехідного шару телурид вісмуту-дітелурид нікелю рівної 40 мкм електричний контактний опір змінюється в інтервалі від* $1.28\cdot10^{-6}$ *до* $3.46\cdot10^{-6}$ *Ом·см*^{2}*, а тепловий – в інтервалі від 0.131 до 0.195 К·см*^{2}*/Вт. З часом цей шар може рости, і, наприклад, за загальної товщини 200 мкм його електричний контактний опір змінюється у тому самому температурному інтервалі від* $6.40\cdot10^{-6}$ *до* $1.73\cdot10^{-5}$ *Ом·см*^{2}*, а тепловий – в інтервалі від 0.655 до 0.975 К·см*^{2}*/Вт. Це зростання істотно впливає не лише на споживчі характеристики, а й на надійність, довговічність та ресурсну стійкість термоелектричних перетворювачів енергії.*

Поряд з цим показано, що композит дітелурид нікелю – телурид вісмуту не є високоефективним термоелектричним матеріалом, але безрозмірна термоелектрична ефективність композиту телурид вісмуту – висоелектропровідні металеві кластери може стати істотно більшою. Знайдено граничну безрозмірну термоелектричну ефективність такого композиту. Бібл. 9 , рис. 5.

Ключові слова: контактний опір, нестаціонарна дифузія, інтерметалід, термоелектричний матеріал, легування, металізований композит, поріг перколяції, нанокластери, оптимальний склад композиту, гранична безрозмірна термоелектрична ефективність, високотемпературна надпровідність.

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О ВЛИЯНИИ ИНТЕРМЕТАЛЛИДОВ НА ЭЛЕКТРИЧЕСКОЕ И ТЕПЛОВОЕ КОНТАКТНЫЕ СОПРОТИВЛЕНИЯ ТЕРМОЭЛЕКТРИЧЕСКИЙ МАТЕРИАЛ - МЕТАЛЛ

Показано, что электрическое и тепловое контактные сопротивления термоэлектрический материал (ТЭМ) – металл в структурах с антидиффузионными слоями существенно возрастают, если переходный контактный слой состоит из подслоя интерметаллида и подслоя композита ТЭМ - интерметаллид. В паре теллурид висмута - никель таким доминантным интерметаллидом является $NiTe_2$*. При общей толщине переходного слоя теллурид висмута-дителлурид никеля равной 40 мкм в температурном интервале 200 – 400 К его электрическоеое контактное сопротивление изменяется в интервале от* $1.28\cdot10^{-6}$ *до* $3.46\cdot10^{-6}$ *Ом·см*^{2}*, а тепловое - в интервале от 0.131 до 0.195 К·см*^{2}*/Вт. Со временем этот слой может расти, и, например, при общей толщине 200 мкм его электрическое контактное сопротивление изменяется в том же температурном* *интервале от 6.40 · 10^{-6} до 1.73 · 10^{-5} Ом·см ^{2}, а тепловой - в интервале от 0.655 до 0.975 К·см^2/Вт. Этот рост существенно влияет не только на потребительские характеристики, но и на надежность термоэлектрических преобразователей энергии. Наряду с этим показано, что композит дителлурид никеля - теллурид висмута не является высокоэффективным термоэлектрическим материалом, но безразмерная термоэлектрическая эффективность композита теллурид висмута - высоэлектропроводные металлические кластеры может стать существенно больше. Найдена предельная безразмерная термоэлектрическая эффективность такого композита. Библ. 9, рис. 5.*

Ключевые слова: контактное сопротивление, нестационарная диффузия, интерметаллиды, термоэлектрический материал, легирование, металлизированный композит, порог перколяции, нанокластеры, оптимальный состав композита, предельная безразмерная термоэлектрическая эффективность, высокотемпературная сверхпроводимость.

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DESIGN OF THERMOELECTRIC GENERATOR FOR TRANSPORT HIGH-POWER STARTING PREHEATER

A physical model of an autonomous system for pre-start heating of vehicles is considered, in which a preheater and a thermoelectric generator providing the system with electric energy are combined by one hydraulic circuit. The results of evaluating the energy characteristics of thermoelectric generators for such systems and the expected values of the efficiency and total thermal power of systems for various serial heaters with a thermal power of more than 15 kW are given. Bibl. 29, Fig. 1, Table 1.

Key words: пstarting preheater, thermoelectric generator, physical model, efficiency.

Introduction

To overcome the difficulties related to the operation of vehicles at low temperatures, starting preheaters are increasingly used - flame heat sources operating from vehicle fuel and heating the engine coolant [1, 2]. At the same time, an effective method for solving the problem of discharging the storage battery of vehicles during the operation of starting preheaters is the use of a thermoelectric generator operating from the heat of the heater and providing autonomous power supply to its components [3 – 8]. In addition, the excess electrical energy from the thermogenerator can be used to recharge the battery and power other equipment.

At the Institute of Thermoelectricity, an experimental model of a thermoelectric starting preheater with a thermal power of 3.5 kW and a maximum electrical power of 100 W has been created for heating vehicles with an engine capacity of up to 4 liters [9 – 11]. Experimental studies of the heater at low temperatures have confirmed the efficiency of the design and proved its effectiveness as a pre-start source of heat for the engine and a source of electricity for heater components. [12]

A preliminary analysis [13] indicates the prospects for such applications to improve the operational capabilities of high-power vehicles, including armoured vehicles.

The purpose of this work is to assess the energy characteristics of the "thermoelectric generator – preheater" system for high-power vehicles and to determine the necessary parameters of thermoelectric generators that make it possible to make such a system autonomous and prevent the discharge of vehicle batteries.

Physical model of “thermoelectric generator-starting preheater” system

The most attractive in terms of efficiency and ease of operation is "thermoelectric generator-preheater" system, in which the preheater and TEG are combined by a single hydraulic circuit. As a thermoelectric generator for this case, a separate thermoelectric preheater of lower thermal power can be used, the electric power of which is sufficient to power the main preheater. Such a heater can be installed separately, in an accessible place of the vehicle, which makes it easier to implement. Fig. 1 shows a physical model of such system for preheating of engines.

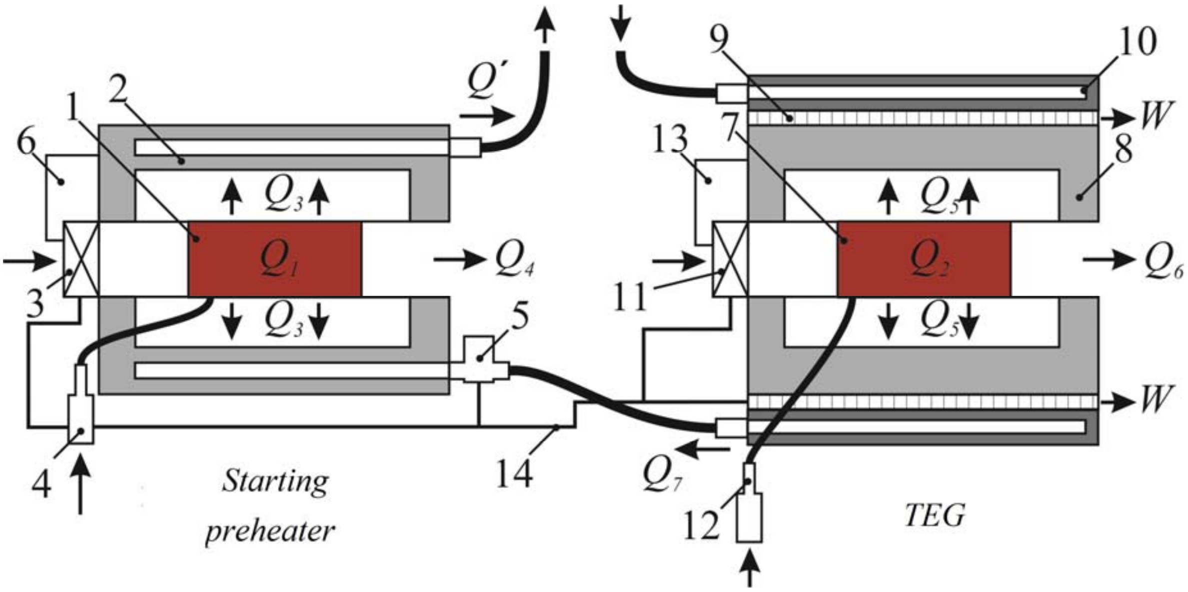

Fig. 1. Physical model of “starting preheater—thermoelectric generator” system :
1 –starting preheater burner; 2 – heat exchanger;
3 – starting preheater air fan; 4 – starting preheater fuel pump;
5 – circulation pump; 6 – starting preheater electronic unit;
7 – thermogenerator burner; 8 –hot heat exchanger;
9 –thermopile; 10 – cold liquid heat exchanger;
11 – thermogenerator air fan; 12 –thermogenerator fuel pump;
13 – thermogenerator electronic unit; 14 – electric connection means.

Liquid starting preheater is composed of heat source 1 which is in the internal volume of heat exchanger 2. As a heat source, a flame burner was used, air and fuel to which are supplied by a fan 3 and a pump 4. In the heat exchanger of the heater, channels are made in which the heat carrier is heated, following which, by pumping with the circulation pump 5, it enters the car engine. Starting and controlling the operation of starting preheater components (air fan, fuel pump, circulation pump) is carried out by the electronic unit 6.

The thermoelectric generator contains an individual flame burner 7, a hot heat exchanger 8 for supplying heat to the thermopile 9, a fan 11 and a heat removal system composed by liquid heat exchangers 10 in which heat carrier is circulating.

Fuel and air delivery to the heat source of thermogenerator is performed by fan 12 and fuel pump 13. An electronic unit 13 is provided in the model of TEG for stabilization of thermogenerator output voltage and control of its work.

The thermoelectric generator in such a system operates as follows. The thermal energy resulting from the combustion of fuel heats the hot heat exchanger, passes through the thermopile and is removed through liquid heat exchangers where heat carrier is circulating, to the hydraulic circuit common with starting preheater. Due to the temperature difference between the hot and cold sides of the thermopile, an electric current is generated to power the preheater, as well as all electrical elements of the generator itself.

Thus, the system under consideration provides the starting preheater with the necessary electric energy, practically without using a battery. However, such a system can also perform additional functions, e.g. a thermogenerator can be used as an auxiliary source of electrical energy in a vehicle.

Results of calculation of the energy characteristics of thermoelectric generator for high-power autonomous pre-start heating system

The efficiency η for the "preheater-thermoelectric generator" system can be introduced as the ratio of the received useful energy to the consumed thermal energy *Q*. Useful energy will be considered the received thermal energy *Q* ', which is directly used for preheating the engine, and electrical energy *W*, which is required for the operation of the system:

$$\eta = \frac{Q' + \sum_i W_i}{Q}, \tag{1}$$

where W_i are powers of electric energy system consumers.

The consumed thermal energy of the system will be equal to the total thermal energy of the burners of the preheater and the thermoelectric generator (TEG):

$$Q = Q_1 + Q_2, \tag{2}$$

where Q_1 and Q_2 are thermal energies of the burners of the preheater and thermal generator that can be expressed by the following relations:

$$Q_1 = \eta_{A1} \cdot A \cdot m_1 \tag{3}$$

$$Q_2 = \eta_{A2} \cdot A \cdot m_2 \tag{4}$$

where η_{A1}, η_{A2} is efficiency of burners of the preheater and TEG; *A* is calorific value of fuel used to operate the system; m_1, m_2 is fuel consumption of the preheater and heat generator, respectively.

Part of the heat Q_1 is used to heat the circulating fluid Q_3, the other part Q_4 is carried by the combustion products into the environment. A similar heat distribution takes place in the thermoelectric generator, namely, part of the heat Q_5 from the burner 7 through the thermopiles 9 is transferred to the liquid heat sinks 10 and discharged into the general heating circuit of the circulating fluid Q_7. The rest of the heat Q_6 is removed from the heat generator by combustion products.

So, expression (1) for system efficiency will be re-written as follows:

$$\eta = \frac{Q_3 + Q_7 + W}{Q_1 + Q_2}, \tag{5}$$

where useful heat Q_7 can be found from heat balance equation:

$$Q_2 = W + Q_7 + Q_6 \tag{6}$$

To assess the efficiency of the system shown in Fig. 1, the characteristics of serial preheaters of different companies, given on their websites and in the operating instructions [14 - 27], were used.

For instance, starting preheater DBW 350 of company Webasto (diesel version, $A = 43$ MJ/kg) has thermal power $Q_3 = 35$ kW and power consumption $m_1 = 4.4$ l/hour [15].

The output electric power of thermal generator is $W = 394$ W: 170 W – for powering the components of starting preheater, 209 W – for powering the circulation pump and 15 W for power supply to the components of TEG.

The value of thermal energy Q_2 can be estimated by the following ratio:

$$\eta_{TEG} = \frac{W}{Q_2}, \tag{7}$$

where η_{TEG} is the efficiency of thermoelectric generator.

Since the thermal energy Q_2 is used to heat the circulating fluid in the common hydraulic circuit, the efficiency of the system will not depend on the efficiency of the thermoelectric generator, and, consequently, on the efficiency of the thermoelectric modules used in the generator. This opens up the possibility to reduce the cost of the generator by using cheaper modules with lower efficiency, which is an important difference of the thermoelectric generator for the transport preheater from the generators for other applications.

To estimate the efficiency of the system, we can take into account that the efficiency of modern TEGs, where single-stage modules based on bismuth telluride are used, is ~ 3.5% [28]. Therefore, to provide the specified output electric power, it is necessary to spend approximately $Q_2 = 11.3$ kW of heat. Given that the amount of heat Q_6 lost with the combustion products in the designs of thermoelectric generators is on average 25% of the thermal power Q_2 [29], we find the amount of thermal energy Q_7 ($Q_7 = 8.4$ kW) consumed to heat the heat carrier and the approximate efficiency of this system ($\eta \sim 80\%$). Results of calculations for this and other variants of starting preheaters are given in Table.

<u>*Table*</u>

Results of calculations of the energy characteristics of “thermoelectric generator – starting preheater” system

Specifications of high-power serial starting preheaters [13 –26]				Calculation results		
Model of starting preheater	Output thermal power of the heater, kW	Electric power consumption of the heater, W	Fuel flow rate of the heater, l/hour	Output thermal power of TEG, kW	Total thermal power of “TEG-heater” system, kW	Efficiency of “TEG-heater” system, %
Webasto (Germany) DBW 160	16	194*	2.3	4.5	20.5	71.9
Webasto (Germany) DBW 230	23.3	214*	3.0	4.9	28.2	78.4
Webasto	30	339**	4.0	7.6	37.6	76.2

Specifications of high-power serial starting preheaters [13 –26]				Calculation results		
Model of starting preheater	Output thermal power of the heater, kW	Electric power consumption of the heater, W	Fuel flow rate of the heater, l/hour	Output thermal power of TEG, kW	Total thermal power of “TEG-heater” system, kW	Efficiency of “TEG-heater” system, %
(Germany) DBW 300						
Webasto (Germany) DBW 350	35	379**	4.4	8.4	43.4	79.9
Eberspächer (Germany) Hydronic L 16	16	164***	2	3.8	19.8	80.2
Eberspächer (Germany) Hydronic L 24	24	184***	2.9	4.3	28.3	82.7
Eberspächer (Germany) Hydronic L 30	30	315****	3.7	7.1	37.1	81.1
Eberspächer (Germany) Hydronic L 35	35	330****	4.2	7.4	42.4	83.0
Teplostar (RF) 14 TC-10	15	132	2	3.2	18.2	76.1
Teplostar (RF) 20 TC-D38	20	200	2.5	4.6	24.6	80.3
Teplostar (RF) APZh – 30D-24	30	336	3.7	7.5	37.5	81.1
SHAAZ (RF) PZhD24B	24	170	3.8	4.0	28.0	65.5
SHAAZ (RF) PZhD 30	30	340	5	7.6	37.6	63.6
SHAAZ (RF) PZhD30G	30	340	5	7.6	37.6	63.6
SHAAZ (RF) PZhD30E	30	340	5	7.6	37.6	63.6
SHAAZ (RF) PZhD30L	30	340	5	7.6	37.6	63.6
SHAAZ (RF) PZhD30M	30	340	5	7.6	37.6	63.6
SHAAZ (RF)	30	140	3.8	3.3	33.3	79.5

Specifications of high-power serial starting preheaters [13 –26]				Calculation results		
Model of starting preheater	Output thermal power of the heater, kW	Electric power consumption of the heater, W	Fuel flow rate of the heater, l/hour	Output thermal power of TEG, kW	Total thermal power of “TEG-heater” system, kW	Efficiency of “TEG-heater” system, %
OZhD30.8106010						
SHAAZ (RF) PZhD44Sh	37	340	8.5	7.6	44.6	47.6
SHAAZ (RF) PZhD600	58	490	11.4	10.8	68.8	54,4
PROHEAT (Canada) M50 12V	15	218*	1.8	5.0	20.0	82.5
PROHEAT (Canada) M50 24V	15	229*	1.8	5.2	20.2	82.5
PROHEAT (Canada) M80 12V	23	206*	3	4.7	27.7	77.5
PROHEAT (Canada) M80 24V	23	229[1]	3	5.2	28.2	77.6
PROHEAT (Canada) M90 24V	26	229*	3.1	5.2	31.2	83.5
PROHEAT (Canada) M105 24V	31	437**	4	9.7	40.7	78.3
PROHEAT (Canada) M125 24V	37	437**	4.2	9.7	46.7	86.4

* – with regard to electric power consumption (104 W) of circulation pump U 4814;
** – with regard to electric power consumption (209 W) of circulation pump U 4851;
*** – with regard to electric power consumption (104 W) of circulation pump Flowtronic 5000;
**** – with regard to electric power consumption (210 W) of circulation pump Flowtronic 6000 SC.

As can be seen from Table 1, the efficiency of "thermoelectric generator - preheater" system for most variants of heaters is at the level of 75-80%. In this case, taking into account the thermal power produced by the heat generator, more powerful modifications of heaters can be replaced by an autonomous system consisting of a less powerful heater and a thermoelectric generator that provides the entire system with electricity. For example, instead of a preheater Hydronic L 35 with a thermal power of 35 kW, an autonomous system can be used, which consists of a Hydronic L 30 heater with a thermal power of 30 kW and a thermoelectric generator with a thermal power of 7 kW and an electric one of about 350 W, which is enough to power such a system. For the most powerful starting preheater PZhD600 among those listed in the table with a thermal power of 58 kW, the thermoelectric generator must have a useful thermal power of 11 kW and an electric one - 0.5 kW (with the efficiency of the thermoelectric generator ~ 3.5%). The total thermal power of such a system will be about 70 kW, which is sufficient for use in armoured vehicles.

The above estimates of energy characteristics of thermoelectric generators are the basis for designing such a generator for a specific variant of the preheater.

Conclusions

1. The energy characteristics of thermoelectric generators for autonomous preheating systems of high-power vehicles are evaluated. The expected values of efficiency and total thermal power of the "thermoelectric generator – preheater" systems for serial heaters with a thermal power over 15 kW are determined.
2. It is established that the efficiency of the "thermoelectric generator - preheater" system for most variants of heaters is at the level of 75-80%. In this case, taking into account the heat output produced by the heat generator, more powerful modifications of heaters can be replaced by an autonomous system consisting of a less powerful heater and a thermoelectric generator that provides the entire system with electricity.
3. It is obtained that a preheater with a thermal power of 58 kW (for example, type PZhD600) can be used to provide the vehicle with thermal energy up to 70 kW, combined into one hydraulic circuit with a thermoelectric generator with a thermal power of 11 kW. In this case, the electricity consumed by the system (0.5 kW) will be fully provided by the heat generator.

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ПРО ПРОЕКТУВАННЯ ТЕРМОЕЛЕКТРИЧНОГО ГЕНЕРАТОРА ДЛЯ ТРАНСПОРТНОГО ПЕРЕДПУСКОВОГО НАГРІВАЧА ВЕЛИКОЇ ПОТУЖНОСТІ

Розглянуто фізичну модель автономної системи для передпускового розігріву транспортних засобів, у якій передпусковий нагрівник і термоелектричний генератор, що забезпечує систему електричною енергією, об'єднані одним гідравлічним контуром. Наведено результати оцінки енергетичних характеристик термоелектричних генераторів для таких систем та очікувані значення ККД та загальної теплової потужності систем для різних серійних нагрівників тепловою потужністю понад 15кВт. Бібл. 29, рис. 1, табл. 1.

Ключові слова: передпусковий нагрівник, термоелектричний генератор, фізична модель, ефективність.

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О ПРОЕКТИРОВАНИЕ ТЕРМОЭЛЕКТРИЧЕСКОГО ГЕНЕРАТОРА ДЛЯ ТРАНСПОРТНОГО ПЕРЕДПУСКОВОГО НАГРЕВАТЕЛЯ БОЛЬШОЙ МОЩНОСТИ

Рассмотрена физическая модель автономной системы для предпускового разогрева транспортных средств, в которой предпусковой отопитель и термоэлектрический генератор, обеспечивающий систему электрической энергией, объединенные одним гидравлическим контуром. Приведены результаты оценки энергетических характеристик термоэлектрических генераторов для таких систем и ожидаемые значения КПД и общей тепловой мощности систем для различных серийных нагревателей тепловой мощностью более 15кВт. Библ. 29, рис. 1, табл. 1.

Ключевые слова: предпусковой отопитель, термоэлектрический генератор, физическая модель, эффективность.

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THERMOELECTRIC AIR CONDITIONERS FOR TANKS

The paper presents the results of studies on the possibility of using thermoelectric air conditioners to provide conditions for the tank crew, which is an important prerequisite for their combat missions. Bibl. 21, Fig. 1.

Key words: thermoelectric air conditioner, tanks, efficiency.

Introduction

General characterization of the problem. In modern armoured vehicles, in particular tanks of the leading countries of the world, air conditioning is actively used to ensure the working conditions of the crew. Particularly relevant is the use of such air conditioners at elevated ambient temperatures. The analysis of the literature shows that the presence of people under elevated ambient temperatures for a long time significantly reduces the efficiency of their work and, with a significant rise in temperature, there is even a risk of loss of consciousness. This jeopardizes the ability to perform combat missions. On the other hand, with a sharp decrease in air temperature inside the tank, there is a risk of acute respiratory diseases, which also reduces the efficiency of the tank crew [1].

The literature mentions the possibility of air conditioning in vehicles, in particular armoured vehicles, by various methods [2 – 8]. Particular attention is paid to the use of compression air conditioners. This is due to their relatively high efficiency. However, they also have a number of disadvantages, in particular, the presence of environmentally hazardous refrigerants, low reliability, sensitivity to mechanical overloads and spatial orientation, which significantly reduces the attractiveness of using such air conditioners. This situation is especially relevant when using these air conditioners in military equipment, due to the presence of increased requirements for its reliability. These disadvantages are eliminated by using thermoelectric conditioners [8, 19, 20].

The analysis of the literature shows that thermoelectric air conditioners are most widely used in the Russian Federation. All serial models of Russian tanks (including export models), starting with the T-90M "Proryv-3" (in service since 2018), are equipped with thermoelectric air conditioners manufactured by JSC Scientific and Production Corporation "Uralvagonzavod" named after F.E. Dzerzhinsky "(Russian Federation) [9, 10]. In addition, CJSC "Konditsioner" (Russian Federation) carries out mass production of thermoelectric conditioners for T-14 Armata tanks [11].

Active studies of thermoelectric air conditioning of tanks under high temperature conditions are underway in India [12, 13]. The thermoelectric air conditioner was integrated into Arjun's main Indian battle tank (in service since 2006) and successfully demonstrated at the Avad Main Research Laboratory (CVRDE), India and at the Mahajan Field Range in Rajasthan (Indo-Pakistan border) in June 2005 [13].

The development of thermoelectric air conditioners for military equipment (including tanks) is also underway in leading countries around the world, including companies like EIC Solutions Inc. (USA) [14], TECA Corporation (USA) [15], Marlow Industries, Inc. (USA) [16], Global Thermoelectric, Inc. (Canada) [17].

The above models of air conditioners have a number of drawbacks, in particular, a rather low coefficient of performance, which worsens their competitive capabilities in comparison with compression refrigerators.

The purpose of this work is to investigate the possibility of using thermoelectric air conditioners to provide conditions for the tank crew, which is an important prerequisite for their combat missions.

Physical model

Physical model of a thermoelectric air conditioner for tanks is presented in Fig.1.

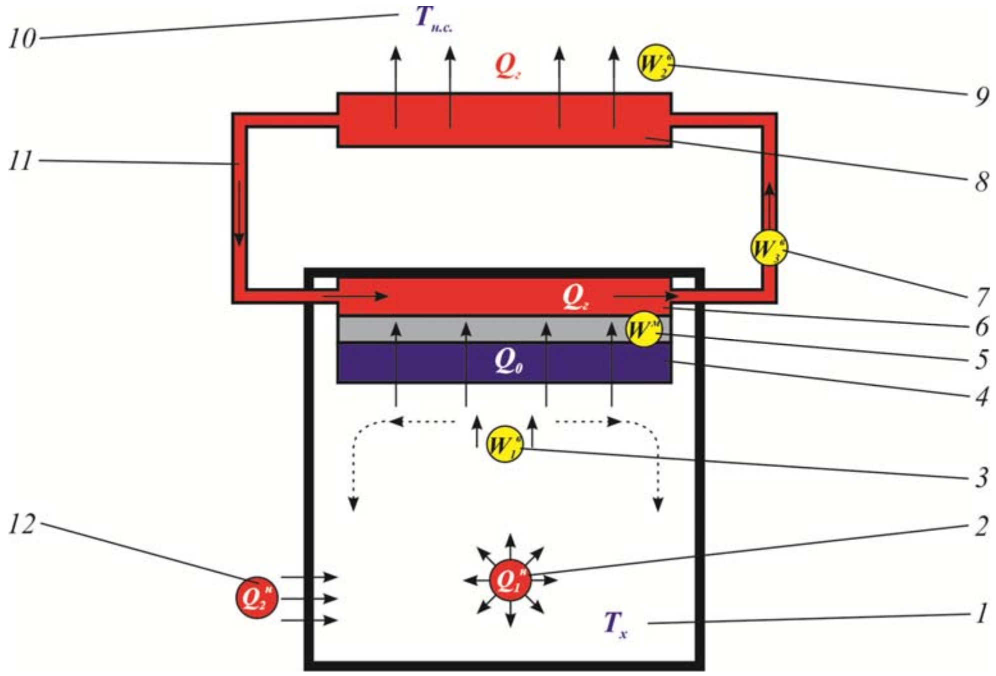

Fig. 1 Physical model of a thermoelectric air conditioner for tanks:
1 – cooled volume, 2 –release of heat Q_1 *inside the cooled volume,*
3 – air fan that consumes electric power W_1*, 4 – cold air heat exchanger of the internal unit of thermoelectric air conditioner, 5 –thermoelectric energy converter that consumes electric power W,*
6 – hot liquid heat exchanger of the internal unit of thermoelectric air conditioner,
7 – liquid pump that consumes electric power W_3*, 8 – liquid-air heat exchanger of the external unit of thermoelectric air conditioner, 9 – air fan that consumes electric power* W_2*,*
10 – environment, 11 – liquid heat carrier, 12 – heat inleak Q_2 *through insulation.*

It consists of two parts - an internal unit inside the tank which provides heat removal from the cooled volume 1, and an external unit which is located on the outer surface of the tank and serves to dissipate the heat flow into the environment 10. The internal unit of the air conditioner consists of a system for transferring heat flow from the cooled volume 1 to thermoelectric modules 5, which contains an air fan 3 and an air heat exchanger 4, and a system for removing heat flow from thermoelectric modules by a liquid heat exchanger 6 using a liquid pump 7. As a liquid heat carrier 11, a liquid with a low congelation point - antifreeze was used. The external unit of the air conditioner contains an air-liquid heat exchanger 8 with an air fan 9, which ensures the dissipation of the heat flux from the air conditioner into the environment. It should be noted that the source of heat inleak inside the cooled volume 1 is internal heat sources 2 (heat inleak from crew members and equipment working inside the cooled volume) and flows from the environment through the insulation of the tank 12, depending on the quality of thermal insulation and the temperature difference between the internal volume and the environment.

It should be noted that, according to sanitary requirements [1], the temperature difference between the ambient air and the volume of air cooled by an air conditioner should not exceed 15 K. However, depending on the value of the ambient air temperature, this difference is different [1]. These requirements were also used in the calculations.

Mathematical and computer description of the model

To describe heat and electricity flows, we use the laws of conservation of energy

$$div\vec{E} = 0 \tag{1}$$

and electric charge

$$div\vec{j} = 0, \tag{2}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{3}$$

$$\vec{q} = \kappa \nabla T + \alpha T \vec{j}, \tag{4}$$

$$\vec{j} = -\sigma \nabla U - \sigma \alpha \nabla T. \tag{5}$$

Here, $\vec{E}$ is energy flux density, $\vec{q}$ is thermal flux density, $\vec{j}$ is electric current density, U is electric potential, T is temperature, α, σ, κ are the Seebeck coefficient, electric conductivity and thermal conductivity.

With regard to (3) – (5), one can obtain

$$\vec{E} = -(\kappa + \alpha^2 \sigma T + \alpha U \sigma)\nabla T - (\alpha \sigma T + U\sigma)\nabla U. \tag{6}$$

Then the laws of conservation (1), (2) will acquire the form:

$$-\nabla\left[(\kappa + \alpha^2 \sigma T + \alpha U \sigma)\nabla T\right] - \nabla\left[(\alpha \sigma T + U \sigma)\nabla U\right] = 0, \tag{7}$$

$$-\nabla(\sigma \alpha \nabla T) - \nabla(\sigma \nabla U) = 0. \tag{8}$$

These nonlinear differential equations of second order in partial derivatives (7) and (8) determine the distribution of temperature T and potential U in thermoelements.

An equation describing the process of heat transport in the walls of heat exchangers in the steady-state case is written as follows:

$$\nabla(-k_1 \cdot \nabla T_1\ ) = Q_1. \tag{9}$$

where k_1 is thermal conductivity of heat exchanger walls, ∇T_1 is temperature gradient, Q_1 is heat flux.

The processes of heat-and-mass transfer of heat carriers in heat exchanger channels in the steady-state case are described by equations [18]

$$-\Delta p - f_D \frac{\rho}{2d_h} v\left|\vec{v}\right| + \vec{F} = 0, \tag{10}$$

$$\nabla(A\rho\vec{v}) = 0, \tag{11}$$

$$\rho \mathrm{AC_p} \vec{v} \cdot \nabla T_2 = \nabla \cdot Ak_2 \nabla T_2 + f_D \frac{\rho A}{d_h}\left|\vec{v}\right|^3 + Q_2 + Q_{wall}, \tag{12}$$

where p is pressure, ρ is heat carrier density, A is cross-section of the tube, $\vec{F}$ is the sum of all forces, C_p is heat carrier heat capacity, T_2 is temperature, $\vec{v}$ is velocity vector, k_2 is heat carrier thermal conductivity, f_D is the Darcy coefficient, $d = \frac{4A}{Z}$ is effective diameter, Z is perimeter of tube wall, Q_2 is heat which is released due to viscous friction [W/m] (per unit length of heat exchanger), Q_{wall} is heat flux coming from the heat carrier to the tube walls [W/m]

$$Q_{wall} = h \cdot Z \cdot \left(T_1 - T_2\right), \tag{13}$$

where h is heat exchange coefficient which is found from equatio

$$h = \frac{Nu \cdot k_2}{d}. \tag{14}$$

The Nusselt number is found with the use of the Gnielinski equation ($3000<Re<6\cdot 10^6$, $0.5<Pr<2000$)

$$Nu = \frac{\left(\frac{f_d}{8}\right)\left(Re - 1000\right)Pr}{1 + 12.7\left(\frac{f_d}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)}, \tag{15}$$

where $Pr = \frac{C_p \mu}{k_2}$ is the Prandtl number, μ is dynamic viscosity, $Re = \frac{\rho v d}{\mu}$ is the Reynolds number.

The Darcy coefficient f_D is found with the use of the Churchill equation for the entire spectrum of the Reynolds number and all the values of e/d (e is roughness of wall surface)

$$f_D = 8\left[\frac{8}{Re}^{12} + \left(A + B\right)^{-1.5}\right]^{1/12}, \tag{16}$$

where $A = \left[-2.457 \cdot \ln\left(\left(\frac{7}{Re}\right)^{0.9} + 0.27\left(e/d\right)\right)\right]^{16}$, $B = \left(\frac{37530}{Re}\right)^{16}$.

Solving Eqs. (7) – (12), we obtain the distributions of temperatures, electric potential (for thermoelements), velocities and pressure (for heat carrier).

The above differential equations with the respective boundary conditions were solved using Comsol Multiphysics package of applied programs.

Design results

An analysis of existing types of tank air conditioners [2-7] shows that the amount of heat flow to be discharged from the internal volume of the tank into the environment is 3 kW. At the same time, the highest regulated ambient temperatures can reach 500C. As noted earlier, according to sanitary requirements [1], the temperature difference between the ambient air and the volume of air cooled by an air conditioner should not exceed 10-15 K, depending on the ambient temperature.

In accordance with the specified requirements and the proposed physical model of the thermoelectric air conditioner, the energy characteristics of the air conditioner were calculated taking into account the energy consumption for ensuring heat transfer conditions.

Thus, to provide the required cooling capacity 3 kW at ambient temperatures up to 50 C and a temperature difference of~ 15 K, a power output of 2.5 kW is required, which corresponds to the energy efficiency value of $\varepsilon \approx 1.2$.

Comparison of the design results with the parameters of known thermoelectric air conditioners for tanks [2 – 7] shows their advantages in energy efficiency by 20-40%, which opens up good prospects for their practical use.

It should be noted that the requirements to be able to operate at elevated ambient temperatures are easily realized with the use of thermoelectric air conditioners (as opposed to using compression coolers), since with a rise in ambient temperature while maintaining the temperature difference, the efficiency of thermoelectric conditioners even grows [20].

In addition, an important advantage of thermoelectric air conditioners is the possibility of using them in heating mode, with their energy efficiency even increasing [21].

Conclusions

1. Physical, mathematical and computer models of thermoelectric air conditioner for tanks have been developed.
2. Design of thermoelectric air conditioner for tanks was performed with regard to requirements for their operation. Thus, to assure the required cooling capacity 3 kW at ambient temperature up to 50 C and temperature difference ~ 15 K, the required electric power is 2.5 kW, which corresponds to energy efficiency $\varepsilon \approx 1.2$.
3. Comparison of the design results with the parameters of known thermoelectric air conditioners for tanks shows their energy efficiency advantages by 20-40%, which opens up good prospects for their practical use.
4. It is determined that the energy efficiency of thermoelectric air conditioners is higher under the conditions of elevated ambient temperatures and when used in heating mode.

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ПРО ТЕРМОЕЛЕКТРИЧНІ КОНДИЦІОНЕРИ ДЛЯ ТАНКІВ

У роботі наводяться результати досліджень можливостей використання термоелектричних кондиціонерів для забезпечення умов перебування екіпажу танку, що є важливою передумовою виконання ними бойових завдань. Бібл. 21, рис. 1.

Ключові слова: термоелектричний кондиціонер, танки, ефективність.

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О ТЕРМОЭЛЕКТРИЧЕСКИХ КОНДИЦИОНЕРАХ ДЛЯ ТАНКОВ

В работе приводятся результаты исследования возможностей применения термоэлектрических кондиционеров для обеспечения надлежащих условий пребывания экипажа танка, что является важной предпосылкой выполнения им боевых задач. Библ. 21, рис. 1.

Ключевые слова: термоэлектрический кондиционер, танки, эффективность.

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EFFICIENCY INCREASE OF THERMOELECTRIC COOLING MODULE FOR X-RAY DETECTOR

The paper presents the results of designing a multi-stage thermoelectric cooling module for X-ray detectors. The design of a thermoelectric cooler as a part of X-ray detector is developed and the technique of increase of its energy efficiency is offered. Bibl. 11, Fig. 1.

Key words: computer design, thermoelectric cooling, X-ray detector.

Introduction

General characterization of the problem. Thermoelectric coolers are widely used to ensure optimal operating modes of various radiation detectors [1, 2]. Their use with semiconductor X-ray detectors is especially relevant, which significantly increases their resolution [3-9].

In [3], the results of computer design of a thermoelectric multi-stage cooler for X-ray detector are presented. The optimal geometric dimensions and operating modes of the cooler were determined, which provide the best operating conditions for X-ray detector. However, the analysis of the thermal circuit of a thermoelectric cooler for X-ray detector showed the presence of heat loss, which leads to a decrease in its energy efficiency.

Therefore, the purpose of the work is to analyze the possibilities of increasing the efficiency of a thermoelectric cooler for X-ray detector.

Physical model

For the calculations, we have used the physical model of a thermoelectric cooler as part of X-ray detector presented in Fig. 1. It consists of a housing 2 with a beryllium window 1 through which radiation enters X-ray detector 3. The required temperature and thermal conditions on the surface of X-ray detector are provided by a multi-stage thermoelectric cooler with an electric power W consisting of n- and p-type thermoelectric material legs 9, electrically conductive interconnect plates10, ceramic electrical insulation plates 11 and electrical leads 8. A vacuum is created inside the detector housing 5 to reduce heat losses. The heat flow is removed from the thermoelectric cooler through the base of detector housing 6 and its fixture 7.

Analysis of the thermal circuit of X-ray detector showed that the source of the greatest losses of efficiency of the thermoelectric cooling module (which also leads to a decrease in the maximum temperature difference) are thermal inleaks to the thermoelectric legs of the module cascades due to radiation. In order to reduce these losses, it was proposed to improve the design of the thermoelectric module by introducing additional radiation shields 4 in Fig.1.

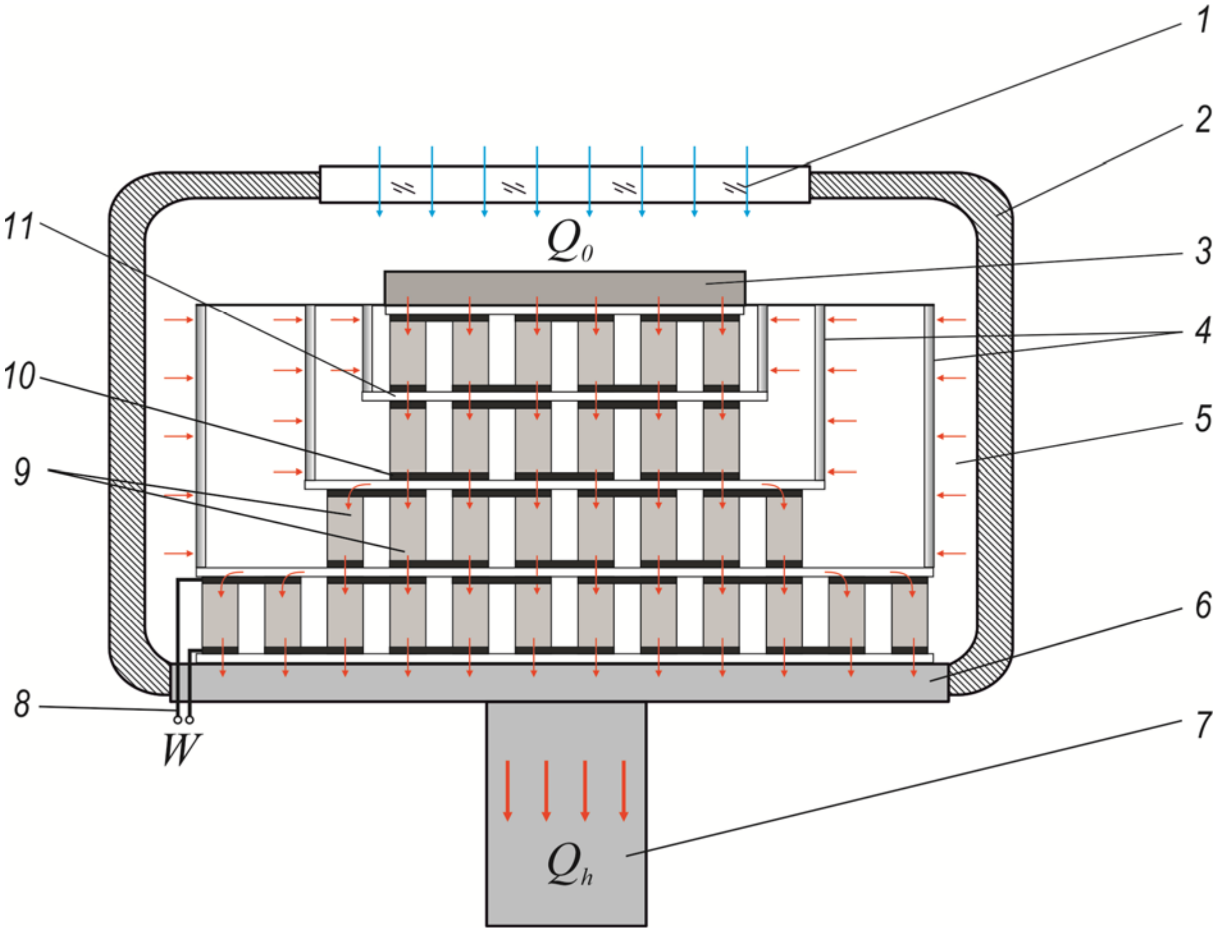

Fig. 1. Physical model of a thermoelectric multi-stage cooler as part of X-ray detector:
1 – beryllium window; 2 – device housing; 3 – X-ray detector;
4 – radiation shields; 5 – internal space of a device where vacuum is created;
6 – device housing base; 7 – device fixture;
8 – electrical leads; 9 – n- and p-type thermoelectric material legs,
10 – electrical interconnect plates, 11 – ceramic electrical insulating plates.

Mathematical and computer descriptions of the model

The system of equations for the description of coefficient of performance of a thermoelectric cooler depending on the parameters of physical model is determined from thermal balance equations:

$$Q_c = \chi_1 (T_c^{(1)} - T_c), \tag{1}$$

$$\begin{cases} Q_h = \chi_3 (T_h^{(2)} - T_h^{(1)}) \\ Q_h = \chi_4 (T_h^{(1)} - T_h) \end{cases}, \tag{2}$$

$$Q_h = Q_\mathrm{c} + W_{TE}. \tag{3}$$

Here, $T_c^{(1)}$ is detector surface temperature, T_c is thermoelectric module cold side temperature, χ_1 is thermal contact resistance, $T_h^{(2)}$ is thermoelectric module hot side temperature, $T_h^{(1)}$ is detector base temperature; T_h is temperature of surface to which heat is removed, χ_2 is thermal contact resistance, χ_3 is thermal resistance of heat exchanger on the “hot side” of thermoelectric converter, Q_0 is refrigerating capacity, Q_h is heating capacity.

With regard to (1) – (3), the expression for the coefficient of performance of thermoelectric cooler will be written in the form:

$$\varepsilon_r = \frac{Q_0}{W + W_1} = \frac{\alpha I(T_c + Q_0 N_1) - 0.5 I^2 R - \lambda(T_h - T_c - (Q_h N_2 + Q_0 N_1))}{W + W_1}, \tag{4}$$

where α is differential Seebeck coefficient of material, I is current strength, R is electrical resistance of thermoelectric module, λ is average thermal conductivity of thermoelectric module legs, W_1 is power consumed to provide heat exchange,

$$N_1 = \frac{(\chi_1 + \chi_2)}{\chi_1 \chi_2}, \; N_2 = \frac{(\chi_3 + \chi_4)}{\chi_3 \chi_4}. \tag{5}$$

To design the thermoelectric cooler, the COMSOL Multiphysics software package was used [10]. For this purpose, the equations of the physical model must be presented in a certain form, as will be shown below.

To describe heat and electricity flows, we use the laws of conservation of energy

$$div\vec{E} = 0 \tag{6}$$

and electrical charge

$$div\vec{j} = 0, \tag{7}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{8}$$

$$\vec{q} = \kappa \nabla T + \alpha T \vec{j}, \tag{9}$$

$$\vec{j} = -\sigma \nabla U - \sigma \alpha \nabla T. \tag{10}$$

Here, $\vec{E}$ is energy flux density, $\vec{q}$ is thermal flux density, $\vec{j}$ is electric current density, U is electric potential, T is temperature, α, σ, κ are the Seebeck coefficient, electrical conductivity and thermal conductivity.

With regard to (8) – (10), one can obtain

$$\vec{E} = -(\kappa + \alpha^2 \sigma T + \alpha U \sigma)\nabla T - (\alpha \sigma T + U\sigma)\nabla U. \tag{11}$$

Then the laws of conservation (5), (6) will take on the form:

$$-\nabla\left[(\kappa + \alpha^2 \sigma T + \alpha U \sigma)\nabla T\right] - \nabla\left[(\alpha \sigma T + U\sigma)\nabla U\right] = 0, \tag{12}$$

$$-\nabla(\sigma \alpha \nabla T) - \nabla(\sigma \nabla U) = 0. \tag{13}$$

The second-order nonlinear differential equations in partial derivatives (12) and (13) determine the distribution of temperature *T* and potential *U* in the thermoelectric cooler.

Solving these equations with the use of technology of object-oriented computer simulation [10] and optimal control theory [11] allows finding optimal design of thermoelectric converter and the dependences of its characteristics.

Computer design results

As a result of computer design of the improved model of the thermoelectric cooler (according to the physical model in Fig. 1), its energy characteristics were calculated and compared with the results of previous studies [2].

Thus, the thermoelectric cooler has 4 stages – each comprising 6, 12, 27 and 65 pairs of legs of thermoelectric material, with its overall dimensions - 12 x 16 x 12 mm while providing the cooled area 4 x 8 mm. The dimensions of thermoelectric material legs based on n- and p-type bismuth telluride (Bi_2Te_3) - 0.6 x 0.6 x 1.8 mm. Electrical insulating plates are made of alumina (Al_2O_3) 0.5 mm thick, electrical connections are made of copper (*Cu)* with anti-diffusion layer of nickel (Ni) 0.1 mm thick. In addition, the thermoelectric cooler contains radiation shields that have thermal contact with the surface of each stage and provide reduction of heat loss due to radiation.

Comparison of simulation results with previous studies [2] shows that the presence of radiation shields leads to a decrease in heat loss inside the thermoelectric multi-stage module by 30% (Q_0 = 31 mW).

When the temperature at the detector $T_c^{(1)}$ = -70 °C and at the heat sink temperature T_h = +20 ° C, the coefficient of performance of the thermoelectric cooler is $\varepsilon = 0.023$. Therefore, the electric power that will be consumed by such a converter is W ≈ 1.5 W.

Moreover, the use of radiation shields opens up opportunities to increase the maximum temperature difference of the thermoelectric module by 5 K, which is important to ensure optimal operating modes of X-ray detectors.

Conclusions

1. The possibility of increasing the energy efficiency of a thermoelectric cooler for X-ray detector by using radiation shields is revealed.
2. It is established that the presence of radiation shields leads to a decrease in heat loss inside the thermoelectric multi-stage module by 30%.
3. It is determined that when the temperature at the detector is provided $T_c^{(1)}$ = -70 °C and at the heat sink temperature T_h = +20 °C the coefficient of performance of the thermoelectric cooler is $\varepsilon = 0.023$. Therefore, the electric power that will be consumed by such a converter is W ≈ 1.5 W.

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ПРО ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТЕРМОЕЛЕКТРИЧНОГО МОДУЛЯ ОХОЛОДЖЕННЯ ДЕТЕКТОРА РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ

У роботі наведено результати проектування термоелектричного багатокаскадного термоелектричного модуля охолодження рентгенівських детекторів. Розроблено конструкцію термоелектричного охолоджувача у складі детектора рентгенівського випромінювання та запропоновано методику підвищення його енергетичної ефективності. Бібл. 11, рис. 1.

Ключові слова: комп'ютерне проектування, термоелектричне охолодження, рентгенівський детектор.

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О ПОВЫШЕНИИ ЭФФЕКТИВНОСТИ ТЕРМОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ ОХЛАЖДЕНИЯ ДЕТЕКТОРА РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

В работе приведены результаты проектирования термоэлектрического многокаскадного термоэлектрического модуля охлаждения рентгеновских детекторов. Разработана конструкция термоэлектрического охладителя в составе детектора рентгеновского излучения и предложена методика повышения его энергетической эффективности. Библ. 11, рис. 1.

Ключевые слова: компьютерное проектирование, термоэлектрическое охлаждение, рентгеновский детектор.

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Кузь Р.В.

ABOUT THE PECULIARITIES OF PROGRESS IN THE WORKS TO CREATE THERMOELECTRIC RECUPERATORS FOR VEHICLES

The analysis of publications, patents, reports at scientific conferences related to the creation of thermoelectric recuperators for the utilization of heat from vehicles is carried out. Conclusions are made on the prospects for further development of such studies.Bibl. 148, Fig. 5.

Key words: thermoelectric generator, exhaust gas, heat recovery.

Introduction

General characterization of the problem.

The use of thermoelectricity for the utilization of waste heat in order to obtain electrical energy has been and remains the subject of interest of specialists dealing with thermoelectricity for the last almost three decades. Internal combustion engines (ICEs) of vehicles occupy a significant place among the sources of waste heat. Therefore, this interest is understandable, since, despite the efficiency of internal combustion engines, almost 2/3 of the thermal energy (Fig. 1) obtained from burning gasoline or diesel fuel is given to the environment, contributing to the thermal pollution of our planet.

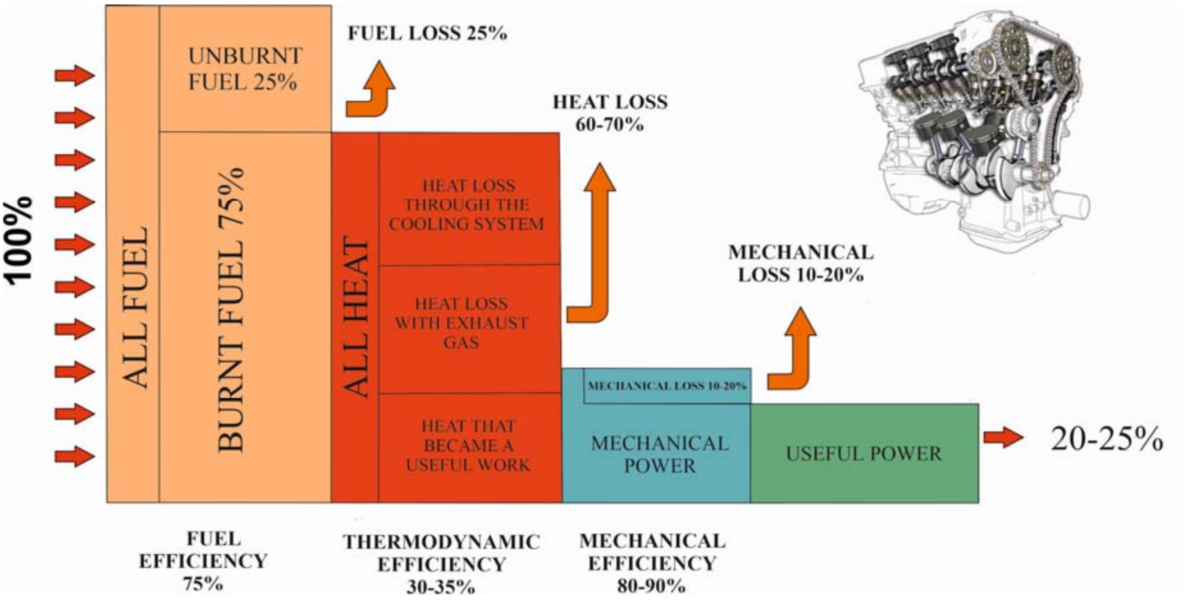

Fig. 1. Energy balance in the internal combustion engine.

The purpose of this work is to analyze the achievements and prospects in the field of thermoelectric recuperators for vehicles.

Progress in the works to create thermoelectric generators (TEG) for vehicles

The geography of research and development of TEG for vehicles covers most of the countries where thermoelectric studies are pursued. More than a hundred reports at many conferences were devoted to the results of such works (Fig. 2).

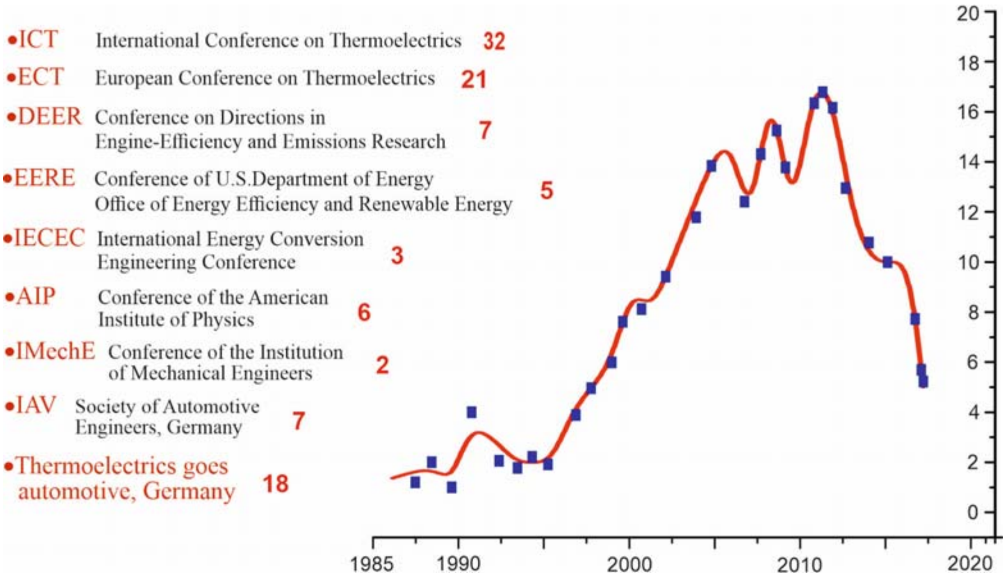

Fig. 2. The dynamics of growth in the number of reports at international conferences on TEG for vehicles [1 - 52].

It should be noted that the peak of research on such thermoelectric generators falls on 2010. After that, there is a decrease in the number of such works. Similar dependences are observed in the number of publications. Their maximum also falls on 2010 with a curtailment of activity in subsequent years (Fig. 3).

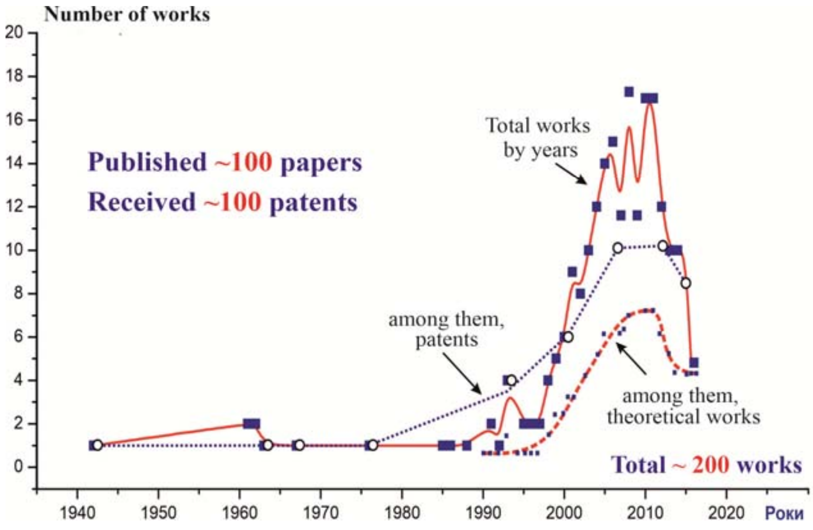

Fig. 3. Dynamics of TEG research activity for vehicles [53 - 148].

The rapid growth in the number of works from the 1990s to the 2010s was the result of hopes for the introduction of automotive thermoelectric generators. However, during this period, in most cases, the samples of generators were developed without proper theoretical justification, simply based on the experience of creating thermogenerators for other purposes - space, autonomous ground, underwater, and so on. About a hundred papers have been published and almost the same number of patents have been received. The result of these efforts was an increase in the power of generators for vehicles up to 1 kW (Fig. 4). Efficiency also increased (Fig. 5), but in the values 8 - 10 times less than expected.

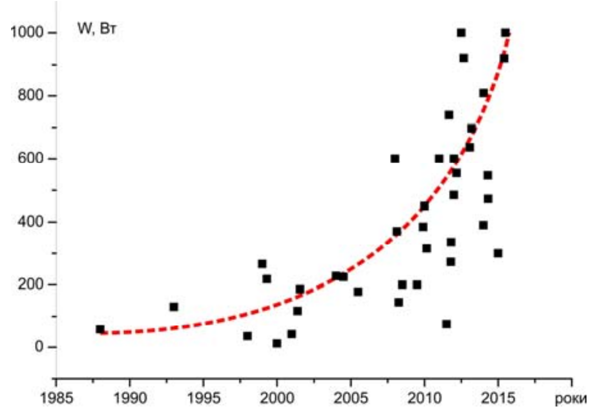

Fig. 4. Growth of TEG power for vehicles.

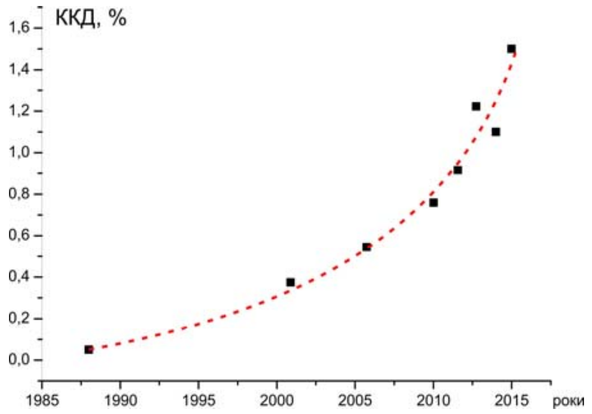

Fig. 5. Growth of TEG efficiency for vehicles.

Nevertheless, the results obtained provided important information about the possibility of using thermogenerators for the utilization of waste heat from vehicles. Let us consider the main ones.

1. It should be recognized that the development of generators for cars is one of the most complex, based on the requirements for them and their properties:
   - restrictions on weight and volume due to their shortage, especially on cars;
   - increased requirements for traffic shaking;
   - significant dependence of thermal power on time leading to increased requirements for the cyclic thermal resistance of generators;
   - lack of stability in electrical voltages and powers, which requires the use of special electronic means to overcome these disadvantages;
   - inefficient use of generators due to their predominant operation in the modes far from maximum power and efficiency;
   - low efficiency values, which cause the high cost of electricity received from generators;
   - restrictions on large-scale use of generators due to insufficient tellurium;
   - heat removal from generators and other problems.
2. The use of thermogenerators in other non-automotive vehicles - diesel locomotives, airplanes, and especially water transport, where the above problems and limitations are less significant looks more promising.
3. In general, progress in thermoelectricity leaves the dream of creating thermoelectric generators for transport vehicles not hopeless. Enthusiasts of this business hope that with a decrease in the cost of generators by 3 -5 times and the provision of their other specific properties, conditions will arise that are promising for their industrial use.

Such results make the idea of creating thermoelectric generators for mass production unattractive, so many of the developers abandoned their further development. In addition, theoretical work led to an understanding of the complexity in the implementation of the idea of thermoelectric generators for cars and became the reason for the curtailment of work in this direction.

Based on these results, it is important in general to consider how promising are further studies in this direction and what real results should be expected in this case.

Conclusions

1. Nonoptimal research and development, when numerous experimental attempts were made without adequate theoretical justification, resulted in an excessive waste of resources and time.
2. The use of TEG on cars is one of the most complex applications of thermoelectricity. Primarily due to a non-stationary heat source, shock and vibration loads, size and weight limitations.
3. A new approach is necessary to consider thermoelectric generators for vehicles, where a thermoelectric generator and an internal combustion engine are jointly considered.

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ПРО ОСОБЛИВОСТІ РОЗВИТКУ РОБІТ ПО СТВОРЕННЮ ТЕРМОЕЛЕКТРИЧНИХ РЕКУПЕРАТОРІВДЛЯ ТРАНСПОРТНИХ ЗАСОБІВ

У роботі проведено аналіз публікацій, патентів, доповідей на наукових конференціях, що стосуються створення термоелектричних рекуператорів для утилізації відходів тепла від трансопртних засобів. Зроблено висновки про перспективи подальшого розвитку таких досліджень. Бібл. 143, рис. 5.

Ключові слова: термоелектричний генератор, вихлопний газ, утилізація тепла.

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О ОСОБЕННОСТИ РАЗВИТИЯ РАБОТ ПО СОЗДАНИЮ ТЕРМОЭЛЕКТРИЧЕСКИХ РЕКУПЕРАТОРА ДЛЯ ТРАНСПОРТНЫХ СРЕДСТВ

В работе проведен анализ публикаций, патентов, докладов на научных конференциях, касающихся создания термоэлектрических рекуператоров для утилизации отходов тепла от трансопртних средств. Сделаны выводы о перспективах дальнейшего развития таких исследований. Библ. 143, рис. 5.

Ключевые слова: термоэлектрический генератор, выхлопной газ, утилизация тепла.

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ON THE USE OF THERMOELECTRIC MICROGENERATORS FOR POWERING CARDIAC PACEMAKERS

The paper describes the design and operation of modern pacemakers, as well as their classification by the mechanism of work and power supplies. A comparative analysis of power supplies is given and prospects for the use of thermoelectric microgenerators for powering pacemakers are determined. Bibl. 66, Fig. 15, Tabl. 8.

Key words: cardiac pacemaker, power supply, thermoelectric microgenerator, cardiovascular diseases.

Introduction

General characterization of the problem. According to the World Health Organization (WHO), cardiovascular diseases (hypertension, coronary heart disease, circulatory disorders, heart failure, and other heart defects) account for one-third of deaths worldwide. It is reported that in 2017 there were more than 400 million people suffering from cardiovascular diseases in the world. Each year, they take more than 17 million lives, and experts predict that by 2030 this number will increase to 23 million people [1].

In the European Region, cardiovascular diseases account for half of all deaths. 80 % of cardiovascular diseases are reported in low- and middle-income countries. According to UNIAN, cardiovascular diseases are the leading cause of death in Ukraine, especially among men. Cardiovascular diseases include ischemic heart disease (heart attacks), stroke, high blood pressure (hypertension), peripheral artery disease, rheumatic heart disease, congenital heart disease and heart failure [2].

Ukraine ranks first in Europe in mortality from cardiovascular diseases. According to the WHO, in 2015, 440 thousand Ukrainians died from cardiovascular diseases, and this figure is increasing annually. Mortality from cardiovascular diseases in Ukraine is 66.3% of the total. Among the diseases of the adult population, cardiovascular diseases lead in the form of hypertension – 41 %, coronary heart disease – 28 %, cerebrovascular diseases – 16 %, etc. [3, 4].

However, the implantation of cardiac pacemakers, artificial heart rhythm drivers, makes it possible to reduce the mortality rate from cardiovascular diseases. About 600,000 cardiac pacemakers are implanted annually worldwide [11], which allows prolonging the life of patients with severe cardiac impairment. Currently, there are various types of cardiac pacemakers (single-chamber, two-chamber, three-chamber and rate-responsive, etc.), the electric power consumption of which varies greatly and ranges from 10 μW to 300 mW. To power such pacemakers, electrochemical galvanic batteries, radioisotope thermoelectric generators, as well as thermoelectric and piezoelectric microgenerators can be used. It should be noted that the most common power supplies for cardiac pacemakers are electrochemical galvanic batteries, whose lifetime is about 10 years, following which it is necessary to replace the electrochemical battery, i.e. perform a second operation. Therefore, the urgent problem is the replacement of galvanic batteries by alternative power sources with a long life [5].

The purpose of this work is to conduct a comparative analysis of power supplies for cardiac pacemakers and to determine the feasibility of using thermoelectric microgenerators.

The structure and operating principle of a cardiac pacemaker

Cardiac pacemaker is an electronic device that performs the function of an artificial heart rhythm driver, which is set for a person in order to restore and normalize heart rhythm disturbances. Cardiac pacemaker is equipped with a special circuit for generating electrical pulses. Most commonly, a cardiac pacemaker is set for bradycardia, atrioventricular blockade, sinus node weakness syndrome [12].

Currently, there are the following basic types of cardiac pacemakers in medical practice: temporary, external and implanted. A modern temporary pacemaker (Fig. 1, 2) is a device that is set when it is necessary to quickly adjust the heart rate (for example, in acute myocardial infarction, as well as some types of bradycardia and tachyarrhythmia). Also, such a pacemaker is used in the pre-operative period with the subsequent implantation of a permanent instrument that replaces the temporary external pacemaker.

Each external pacemaker belongs to the group of temporary pacemakers and is widely used to correct heart rate by various indicators. The design of the external pacemaker provides for the presence of sufficiently large-size electrodes, which are superimposed in the region of the heart on the chest and on the area between the spine and the left shoulder blade (cardiac projection). Modern external pacemakers are in demand in the diagnosis, prevention and urgent restoration of the normal rhythm of heart contractions without surgical intervention [20].

Fig.1. Temporary cardiac pacemaker [12]

Fig.2. External cardiac pacemaker [12]

However, the subject of this work is precisely implanted cardiac pacemakers, so we will consider them in more detail.

In turn, implanted cardiac pacemakers are divided into single-chamber, two-chamber, three-chamber and rate-responsive (intracardiac). The type of device needed for each clinical case is determined by doctor individually, based on the results of diagnostic studies [19-29].

A single-chamber pacemaker has only one active electrode and stimulates only one heart chamber (ventricle or atrium). Such a pacemaker is a simple and inexpensive device that does not have the ability to simulate physiological (natural) contraction of the heart muscle (Fig. 3). To date, such a cardiac pacemaker is accepted to use only with a constant form of pleural arrhythmia, with the electrode installed in the right ventricle.

A two-chamber cardiac pacemaker is connected via electrodes to the atrium and ventricle at the same time (Fig. 4). In the event of a need for stimulation, the generated pulse is sequentially fed first to the atrium, and then to the ventricle. This mode corresponds to the physiological contraction of the myocardium, normalizes cardiac output, ensures the coordinated work of the atrium and ventricle, and also improves the patient's adaptation to physical activity. Additional functions of modern two-chamber cardiac pacemakers make it possible to choose the optimal mode for each patient.

A three-chamber pacemaker (cardiosynchronization) is able to stimulate three chambers of the heart in a certain sequence: the right and left ventricle, as well as the right atrium (Fig. 5). Such cardiac pacemakers ensure the normal functioning of the heart and physiological intracardiac hemodynamics. These cardiosynchronization devices can be used to eliminate desynchronization of the heart chambers in severe forms of bradyarrhythmia or bradycardia. Such devices are implanted in patients with a dangerous form of arrhythmia - ventricular tachycardia and ventricular fibrillation or for the prevention of sudden cardiac death.

A rate-responsive cardiac pacemaker is a tiny device that is implanted completely inside the heart (Fig. 6). Such a pacemaker is equipped with sensors that can record changes in nervous system activity, respiratory rate and body temperature. Cardiac pacemakers of this type are used for cardiac pacing with rigid sinus rhythm, which is provoked by significant heart failure. Such pacemakers can much more accurately determine changes in physical activity and heart rate of the patient than the above two- and three-chamber.

Fig.3. Implanted single-chamber cardiac pacemaker [31]

Fig.4. Implanted two-chamber cardiac pacemaker [31]

Fig.5.Implanted three-chamber cardiac pacemaker [31]

Fig.6. Implanted rate-responsive (intracardiac) pacemaker [31]

An implanted cardiac pacemaker consists of a set of endocardial electrodes, a connector block, a microprocessor, a housing, and a battery (Fig. 7). The electrodes are flexible and durable spiral conductors that are fixed in the chambers of the heart and transmit pulses emitted by the device to the heart and also transmit information about the activity of the heart to the microprocessor. The number of endocardial electrodes depends on the state of the disease and the need to stimulate various parts of the heart.

The connector block is designed to connect the pacemaker housing to the endocardial electrodes. The housing of the device is made of titanium or other alloys that do not interact with the human body. Inside the housing there is a microprocessor, which works offline and is a special device for monitoring and adjusting the settings of the pacemaker. Using highly sensitive sensors, the processor also carries out Holter monitoring and observation of the human heartbeat, interfering with the work of the heart in case of violations.

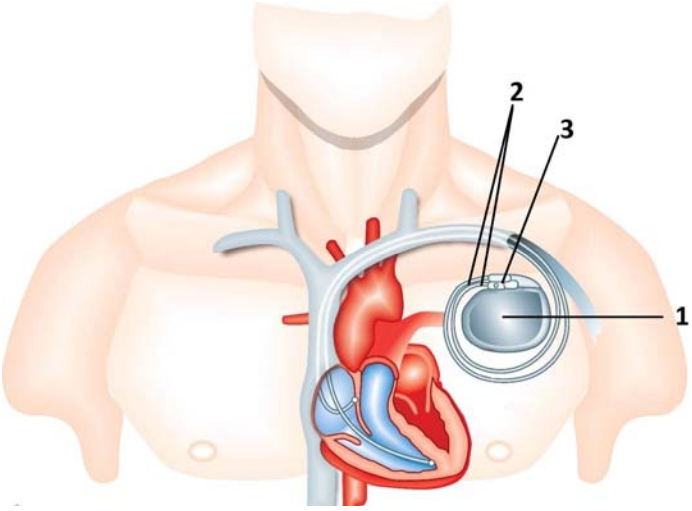


Fig. 7. Design of implanted cardiac pacemaker: 1 – cardiac pacemaker, 2 – endocardial electrodes, 3 – connector block

The main elements of a cardiac pacemaker are endocardial electrodes, used for stimulation, resynchronization or defibrillation of the heart. They consist of several common components, including electrodes, conductors, insulators, locking mechanisms, and connector pins (Fig. 8). Defibrillation openings also include shock coils for delivering high voltage electrical discharges to stop ventricular fibrillation. The number of electrodes depends on the condition of the disease and the need for stimulation of the heart [15]

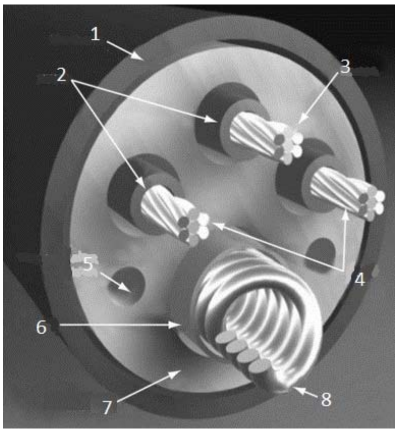


Fig. 8. Design of endocardial electrode [15]:
1 – urethane protective coating, 2 – ETFE (coating), 3 – sensor, 4 – defibrillator,
5 – squeezed clearance, 6 – PTFE(coating), 7 – HP silicone, 8 – electrode

The operating principle of a cardiac pacemaker is to control the heart rate (stimulation or inhibition) and defibrillation of the heart if it stops, by artificially contracting the heart muscles with the help of electrical pulses. Cardiac pacemaker stimulates the human heart by transmitting electrical pulses from the processor through the endocardial electrodes to the heart muscles [16, 17].

The microprocessor of a cardiac pacemaker constantly analyzes the pulses generated by the heart, conducts pulses to the wall of the heart and controls their synchronization. The endocardial electrodes transmit the pulse generated by the pacemaker to the heart chamber and transmit information about the activity of the heart back to the microprocessor. At the end of each endocardial electrode there is a metal nozzle, which provides contact of the electrode with the corresponding part of the heart, and also “reads” information about the electrical activity of the heart and, if necessary, transmits electrical pulses.

With a small number of heart contractions or their complete absence, the cardiac pacemaker switches to the mode of constant stimulation and transmits pulses to the heart with a frequency that was set during implantation of the device. During normal heart function, a cardiac pacemaker starts to work in standby mode and functions only in the absence of independent heart contractions. In modern cardiac pacemaker models, the control of work settings is carried out by a microprocessor, is programmed during implantation and can be changed remotely and without surgical intervention [18].

General requirements for pacemaker power supplies

Over the past 50 years, there has been a rapid evolution of the technology of manufacturing cardiac pacemakers (Fig. 9). The overall dimensions and power consumption of modern cardiac pacemakers have significantly decreased with the simultaneous increase of their functionality. Currently, the most common are single-, two-, and three-chamber cardiac pacemakers implanted in the subcutaneous pocket near the heart, followed by electrode insertion into the heart chambers, and rate-responsive cardiac pacemakers implanted directly inside the heart. The above-mentioned types of cardiac pacemakers are powered by electrochemical galvanic batteries. The power requirements of these cardiac pacemakers are different. A comparative analysis of technical specifications of power supplies for cardiac pacemakers is shown in Table 1.

Fig. 9. Evolution of the technology of manufacturing cardiac pacemakers
Evolution of implanted cardiac pacemakers. 1958 Weight 74.4 g

Table 1

Technical specifications of power supplies for cardiac pacemakers [34,43-46,]

Parameter	Single-, two- and three-chamber cardiac pacemekers	Rate-responsive (intracardiac) cardiac pacemeakers
Dimensions	49 mm x 46 mm x 6 mm	length 42 mm, diameter 5.99 mm
Mass	20-30 g	2-5 g
Operating voltage	1.5-4.7 V	1.5-2 V
Electric power	0.1-370 mW	0.070 mW
Battery capacity	2000 mA	120-248 mA (novel)
Service life	9-10 years	4.7-14.7 years

Table 1 shows that the overall dimensions of electrochemical galvanic power supplies for implanted single-, dual- and three-chamber pacemakers are within 49 mm x 46 mm x 6 mm, and for implanted rate-responsive pacemakers - 42 mm, with a maximum diameter of 5.99 mm. The weight of such power supplies does not exceed 20-30 g and 2-5 g, respectively. The minimum operating voltage is 1.5 V for both types of pacemakers. The electric power consumption of one-, two- and three-chamber cardiac pacemakers is 0.1-370 mW, which significantly exceeds the power consumption of rate-responsive pacemakers, is 0.070 mW. These power supplies provide the necessary electrical power and voltage for 9-10 years for various types of pacemakers. However, the main disadvantage of such power supplies for cardiac pacemakers is the need for their periodic replacement after the end of life (re-operation) and their toxicity. However, the developers predict that in the event of a depleted power supply, the cardiac pacemaker switches to power-saving mode, limiting most of the additional functions in order to save the vital options. In this mode, the cardiac pacemaker can work up to 3 months [10 – 14].

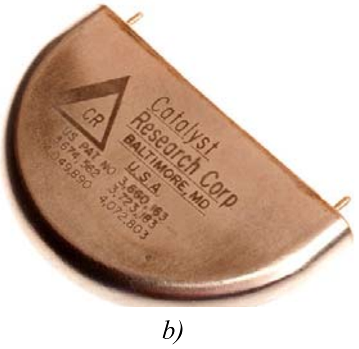
Operating principle and technical specifications of power supplies for cardiac pacemakers

Implanted cardiac pacemakers can have the following power supplies: electrochemical galvanic battery, radioisotope thermoelectric generator, piezoelectric and thermoelectric microgenerators, as well as pendulum actuated [40, 49, 39].

Cardiac pacemakers with electrochemical galvanic battery

Lithium-ion batteries for cardiac pacemakers are tiny power supplies (the weight of a cardiac pacemaker without electrodes, but with a battery is 26-28 grams), the charge of which is enough for about 10 years of continuous operation [34-42]. In practice, there are different types of pacemakers weighing from 20 to 50 grams, and a service life of up to 10 years [21, 22]. The appearance and technical specifications of the pacemakers with electrochemical galvanic battery are shown in Fig. 10 and Table 2.

a)



b)

Fig.10. Cardiac pacemaker with electrochemical galvanic battery [44]:
a) cardiac pacemakers Boston Scientific Accolade on lithium-ion batteries,
b) lithium-ion battery of diameter 30 mm.

Table 2

Technical specifications of cardiac pacemakers with electrochemical galvanic battery

Power supply	Operating voltage	Power	Average dimensions	Manufacturers
Lithium-ion battery	2.2 ÷ 2.8 V	25-30 mW	49 mm × 46 mm × 6 mm	Saint Jude medical, Boston Scientific, Medtronic, Vitatron

Usually, regular visits to the doctor will assess the condition of the power supply to determine the time during which it will still work. If the battery is depleted, the doctor recommends a procedure for the replacement of the cardiac pacemaker. During this procedure, not only the battery but also the entire pacemaker is replaced. Therefore, the operation is very similar to that performed at the first implantation of the device.

Battery life depends on the manufacturer. Modern pacemakers often use more energy because the battery not only sends pulses to the heart, but also regulates pacemakers, stores heart rate information and performs other functions. If the pacemaker is rarely activated, the battery can run for a long time. The batteries in the cardiac pacemaker are depleted quickly if the device has to be regularly activated to support the heart. This is one reason why doctors cannot accurately predict the life of a device. In each case, the battery charge will deplete at different speeds, so each patient's case is individual [28,39-40, 43].

There are also rare cases of implanting a device with a battery that has certain disadvantages. The cardiac pacemaker power supply is carefully tested before implanting the device, however sometimes testing does not reveal an existing problem, and the battery charge decreases abnormally quickly. Another cause of rapid battery depletion may be microprocessor defects or other components of the cardiac pacemaker. This is one of the reasons why the patient needs to visit the doctor repeatedly for several weeks immediately after implanting the device, and to make sure that the device is working properly.

Lithium-ion battery is the cheapest and most compact power supply for cardiac pacemakers, but its main disadvantage is short life.

It should be noted that in 2013, the American startup Nanostim Micra implemented a fundamentally new type of cardiac pacemaker without endocardial electrodes, it was notable for its tiny size and implantation feature (although the patent for a utility model dates back to 1976 [51], a serial advanced model was released only in 2013 [48]). Such cardiac pacemaker is set without surgical intervention - via transvenous access (through the femoral vein) into the chambers of the heart. Experts say that this technological novelty is a grand stride forward, and although it is quite new, it is actively developing [43-49]. The appearance and technical specifications of the rate-responsive cardiac pacemaker are shown in Fig. 11 and Table 3.

Fig.11. Rate-responsive (intracardiac) pacemaker [43-49,52]

Table 3

Technical specifications of the rate-responsive cardiac pacemaker

Power supply	Operating voltage	Power	Dimensions	Manufacturers
Electrochemical galvanic battery based on: • Lithium-carbon monofloride • Lithium-argentum-vanadium oxide	1.5-2 V	70 μW	Length: 13.5-42 mm, diameter: 2.6-5.99 mm	Medtronic, Sant Jude Medical (Nanostim), EBR Systems (CambridgeConsultants)

An incision is made on the patient’s skin to set a standard pacemaker, and then the doctor passes the endocardial electrodes through the lateral vein into the heart. The device itself is placed in a special subcutaneous pocket near the chest. Such a system is far from perfect through the great risks of infection of the subcutaneous pocket, and the presence of a conventional pacemaker limits the patient's mobility and life. In contrast, the Nanostim Micra pacemaker is set by insertion into the femoral vein via a small incision in the groin area, and then transported to the patient's heart by a catheter. The wireless device is equipped with a tiny battery and can operate from 8 to 10 years. The absence of endocardial electrodes and the necessary subcutaneous pocket reduces the possibility of infection and, moreover, patients are not limited in their activity.

A positive perception of intracardiac pacemaker by the human body and a productive life were observed in 280 of 300 patients (93.3 %). After 6 months, serious side effects associated with the device were observed in 6.7 % of patients; cases included device overload during surgical removal (1.7 %), cardiac perforation (1.3 %), which required removal and replacement of the device (1.3 %) [47].

The latest pacemaker models of this type are already equipped with an inductive battery charging system. Animal tests were successful, which gave impetus to the further improvement and implantation of this type of pacemakers. In addition, recharging is fast enough. For example, a battery with a capacity of 1050 mA from 50 to 100 % can be charged in 56 minutes by placing the transmitter at a distance of 10 mm from the patient's chest at a frequency of 13.56 MHz. There are no similar analogues in the market of artificial pacemakers, which makes this type of device the "flagship" of pacing [37, 38].

Cardiac pacemaker with a radioisotope thermoelectric generator

This cardiac pacemaker uses as a power supply a thermoelectric generator with a radioactive isotope heat source. The pacemaker consists of a housing which accommodates a thermoelectric generator and a lead capsule with radioactive uranium or plutonium, as well as a microprocessor, is connected to a set of endocardial electrodes using a connector block. The operating principle of the RITEG is to convert the heat generated from the radioactive decay of uranium into electrical energy using a thermoelectric generator. Unlike lithium-ion battery, the RITEG is more durable (service life is up to 30 years), but it is more large-format [41 – 42]. The appearance and technical specifications of a cardiac pacemaker with a radioisotope thermoelectric generator are shown in Fig. 12 and in Table 4.

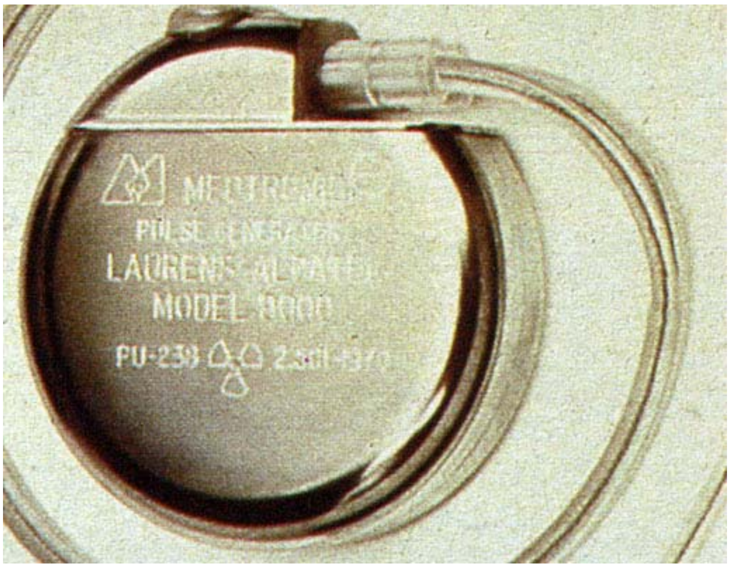


Fig. 12. Cardiac pacemaker with a radioisotope thermoelectric generator [53]

Table 4

Technical specifications of a cardiac pacemaker with a radioisotope thermoleectric generator

Power supply	Operating voltage	Power	Dimensions	Manufacturers
Radioisotope thermoelectric generator (RITEG)	4-4.7 V	300-370 mW	30 × 60 × 40 mm	Medtronic CCC ArcoMedical American Opticals

RITEG were first introduced in the 1970s in order to extend the life of cardiac pacemakers. At that time, such a pacemaker was a good substitute for mercury-zinc batteries, which, in addition to their unreliability, had a very short service life - less than three years. From this standpoint, RITEG, which provided patients with the opportunity to have only one cardiac pacemaker for life, was a good alternative. The first implantation of such a pacemaker, manufactured by Medtronic together with Alcatel, took place in 1970 in Paris [41].

However, in the early 1980s, such batteries slowly began to be displaced by lithium-ion. In those days, the service life of lithium-ion batteries was about 5-10 years. Therefore, the doctors decided that it is better to do the operation at intervals of one decade and to change the device to a newer one, than to walk with an outdated overall device for a lifetime. Therefore, the implantation of cardiac pacemaker with RITEG was discontinued between 1985 and 1990. As of 2003, approximately 100 people lived in the United States who had been implanted cardiac pacemakers with RITEG [42]. Patient status information as of 2019 was not found.

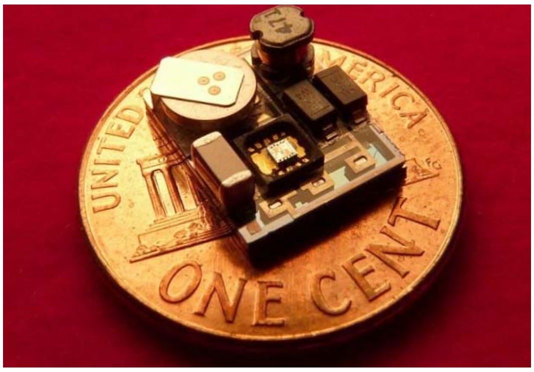
And yet, it should be noted that despite its size, the main drawback of RITEG is toxicity. Patients and their entourage, despite the isolation and protective housing of the cardiac maker, are adversely affected by radioactive radiation [48].

Cardiac pacemaker with a piezoelectric generator

The power supply for such a pacemaker is a piezoelectric element consisting of a housing containing a membrane, quartz plates and electrical terminals through which the generated electricity is transmitted to an electronic amplifier housed inside the pacemaker [59 – 62]. Z-section quartz crystalline elements (along the axis of symmetry) of a piezoelectric element are cropped quartz plates covered by several protective layers - a layer of chromium and Cr-Au gold, a photoresistive layer and a layer of galvanic copper.

Stimulation of the human heart by such a pacemaker is carried out by transmitting electrical pulses from the processor through the endocardial electrodes to the heart muscles [60]. The power supply of such a pacemaker is provided by a piezoelectric element. The principle of its work is to convert the mechanical energy of deformation created by the human breath into electrical energy. Due to the compression of the quartz plates of the piezoelectric element along one of the three symmetry axes, one side of the plate is charged positively and the other negatively.

When the plate restores equilibrium, the phenomenon of the inverse piezoelectric effect is observed: the positively charged side becomes negatively charged, the negatively charged side – vice versa. The magnitude of the electric charge is directly proportional to the magnitude of the pressure on the quartz plates. In this case, longitudinal compression is used, as a result of which compression of the quartz plate on one side leads to charging of this plate on the opposite side. Thus, the power supply of the pacemaker is as follows: the compression of the housing is converted by the membrane into an effort, causing the compression of quartz plates (for example, with a diameter of 5 mm and a thickness of 1 mm). The electric charge generated at the electrical terminals is transmitted to the electronic amplifier and stabilized by means of a voltage stabilizer to the level of 1.5 ÷ 2 V. The appearance and technical specifications of a pacemaker with a kinetic (piezoelectric) generator are shown in Fig. 13 and Table 5.



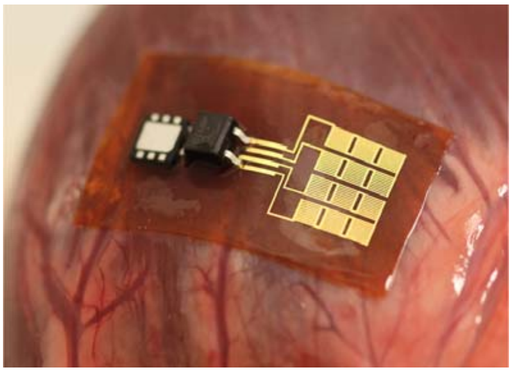


Fig. 13. Piezoelectric generator for cardiac pacemakers [62]

Table 5

Technical specifications of cardiac pacemakers with a kinetic (piezoelectric) generator

Power supply	Operating voltage	Power density and current strength	Dimensions
Piezoelectric generator with crystals (nanolegs) based on: • Zinc oxide (ZnO); • Barium titanate ($BaTiO_3$); • Plumbum zirkonititanate (PZT).	1.5-2 V	7 mW/cm^3 0,19 µA/cm^2	0.1-20 × 0.1-20 × 0.0001 mm

Pacemakers with piezoelectric generators have also been developed that are capable of converting into electricity even the compression energy generated by the motions of the lungs, blood flow, palpitation and vascular contraction. Such piezoelectric generators consist of zinc oxide (ZnO) or barium titanate ($BaTiO_3$) nanolegs. In a generator about 2 mm^2 in size, there are over 1 million nanolegs. The nanowire array is coated with a silicon electrode with a zigzag platinum coating, which is used to increase the electrode conductivity. When chemically grown legs located at the end of the electrode bend are subject to vibration, the ions in them shift. This imbalance creates an electric field that produces electricity and can be used as a potential source of energy. The efficiency of such a piezoelectric generator is 17-30%.

In 2010, scientists at Arizona State University developed miniature piezoelectric generators that can convert heart muscle energy into electrical energy. The research team was able to successfully implant polymer-based piezoelectric generators. The current generated by the generators is enough for powering low-power medical devices, as well as for charging the battery of the set cardiac pacemaker. Experiments have been conducted to show that, at periodic deformation of the device, the voltage at the terminals is from 1 to 2 V and the current is about 100 nA [60] Initial tests on rabbit hearts showed voltages and currents of about 1 mV and 0.2 mA, respectively. Output power is much less than what is needed for the existing pacemakers. However, novel thin-film generators on the basis of barium titanate and plumbum zirkonititanate are much more efficient [60]. The $BaTiO_3$ ferroelectric solid films were deposited by radio frequency magnetron sputtering on a Pt/Ti/SiO_2 /(100) Si substrate and subjected to an electric field of 100 kV /cm. Metal insulators ($BaTiO_3$)-metal-structured tapes were transferred to a flexible substrate and connected by electrodes. During the periodic deformation stage, a flexible $BaTiO_3$-based nanogenerator generates an output voltage of up to 1.0 V. This nanogenerator produces an output current density of 0.19 μA/cm^2 and a power of ~ 7 mW/cm^3. According to scientists, the piezoelectric generator used in this study is able to produce enough electricity to meet all the needs of the cardiac pacemakers [60].

Another option is a piezoelectric nanogenerator based on the legs of plumbum zirconititanate (PZT), which uses a soft polymer silicon substrate. Such a piezoelectric nanogenerator, with a diameter of approximately 60 nm, is capable of generating an output voltage of 1.63 V and an electrical power of 0.03 μW with periodic compression of the soft polymer [61]. The use of such piezoelectric nanogenerators with an extended service life or the complete rejection of batteries in implanted medical devices (cardiac pacemakers) will protect patients from repeated operations and from the risk of postoperative complications (infection, rejection of the implant by the body, etc.).

It has been found experimentally that a piezoelectric generator produces ten times more power than a cardiac pacemaker needs, and its size is about half that of a battery of such implants. In addition, such a piezoelectric generator works regardless of the heart rate - it produces sufficient electric power with a pulse of 20 to 600 beats per minute. The developers also claim that its work is not affected by mobile phones, microwave ovens and other similar devices [61]. It should be noted that piezoelectric generators are promising for powering cardiac pacemakers, but they still do not have wide practical application, since they require a large number of further medical and clinical trials. The service life of the piezoelectric generator is difficult to evaluate, since it depends on the location, voltage, etc., although there is a generator that has been operating since 1982 [63].

Cardiac pacemakers without electrodes, battery-free and mechanically controlled by heart

Swedish scientists Dr. Adrian Zurbuchen, Andreas Heberlin and Lucas Beroiter of the University of Bern in Switzerland in 2016 developed a fundamentally new approach to pacemaker technology. The power source of such a pacemaker is a winding mechanism, which works on the principle of a wristwatch. This device does not have a power supply that must be periodically changed, as well as endocardial electrodes, i.e. it is placed directly on the heart, which does not limit the patient's movement, and is better perceived by the body due to its small size.

The power supply is a mechanism based on the ETA 204 \ ETA SA winding, Grenchen Switzerland. The weight of 12 g was achieved by skeletonization of the body.

The main structural elements are the oscillation weight (pendulum), which is made of platinum alloy (7.5 g), which turns the heartbeat into circular rotation of the pendulum, a mechanical rectifier that allows you to convert energy from the oscillations of the pendulum in both directions, a spiral spring, which is temporarily stores energy in a mechanical form and an electric microgenerator (MG205, Kinetron BV, Netherlands), which converts the energy of rotational motion into an electrical signal. When the torque of the coil spring is equalized with the torque needed to operate the generator, the coil is released and powers the electric micro-generator. The resulting pulse includes about 80 μJ at a load resistance of 1 kΩ [64].

The power supply and electronics of the cardiac pacemaker are combined in a special polymer housing. Two electrodes with a diameter of 0.5 mm and a length of 3 mm are placed at the bottom of the housing and pierce the myocardium. The housing has a diameter of 27 mm and a thickness of 8.3 mm.

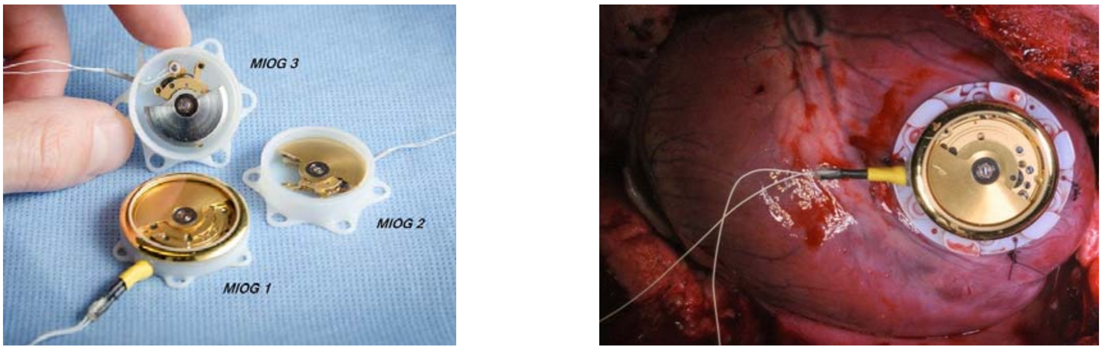


Fig. 14. Cardiac pacemaker mechanically controlled by heart [66]

Table 6

Technical specifications of cardiac pacemakers without electrodes, battery-free and mechanically controlled by heart

Power supply	Operating voltage	Power	Dimensions
Self-winding mechanism (similar to wristwatches)	~3 V	82-90 μW	Diameter 27mm Height 8.3mm

The experimental results showed high output power, especially when placed on the left side of the heart. When placing the device in this position, constant power values of 82 ± 4μW and 90.1 ± 0.7μW were taken, which are reasonably good parameters for power supply. Also, the pacemaker is equipped with a 47μF capacitor, which absorbs excess energy and, in the event of a lack of energy, can supply the pacemaker for a minute [64]. This development is conceptual and requires further improvements, such as increasing the capacity of capacitor, reducing the weight of the pendulum and increasing the power. But despite this, the development is promising.

Cardiac pacemaker with a thermoelectric microgenerator

Such a pacemaker contains a set of endocardial electrodes, a connector block, a thermoelectric microgenerator (TEG), a microprocessor, a capacitor, a voltage stabilizer, and a housing (Fig. 15) [6, 8, 55 – 58]. The thermoelectric microgenerator is a multi-element thermocouple thermoelectric micromodule with two ceramic plates and electrical terminals. The thermoelectric micromodule consists of a set of semiconductor thermocouple elements connected in a series circuit, the gaps between which are filled with an insulating epoxy compound, and two ceramic plates that are tightly in contact with the upper and lower faces of the thermocouple elements, as well as two electrical terminals. Such a thermoelectric micromodule is made on the basis of modern high-performance thermoelectric materials based on *Bi-Te*. The manufacturing technique of such micromodules provides a packing density of up to 5000 legs of *n*- and *p*-type thermoelectric material per 1 cm^2 of micromodule area [8]. For example, a typical thermopile with a total surface area of 1.5 cm^2 generates a voltage of 1.5 V and provides a power of 100 μW at a temperature difference of 1 ° C. The technical specifications of a cardiac pacemaker with a thermoelectric microgenerator are shown in Table 7.

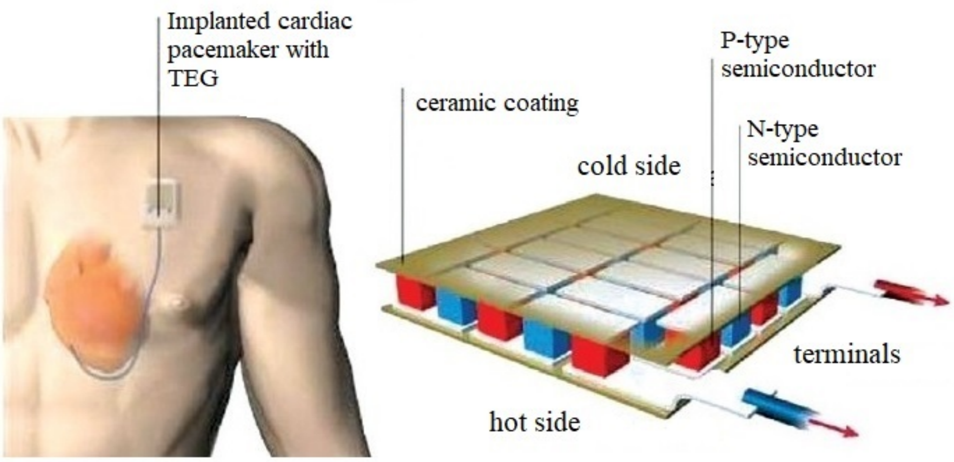


Fig.15. Schematic of implanted cardiac pacemaker with TEG [49,55]

Table 7

Technical specifications of cardiac pacemakers with a thermoelectric microgenerator

Power supply	Operating voltage	Power	Dimensions
Thermoelectric microgenerator	1.5-2 V (at temperature difference 1 °C)	100 µW	10 × 15 × 2 mm

In order to obtain the necessary voltage and power using a thermoelectric micromodule for powering cardiac pacemaker, a temperature difference between its faces should be arranged. To ensure the heat flux through the thermoelectric micromodule, it is necessary to place the thermoelectric converter inside the human body between internal organs having different temperatures, for example, near a vessel through which blood circulates at a temperature of 37 ° C. It should be noted that the temperature differences between the internal organs of a person reach 0.5-1 ° C, which is quite enough to generate the necessary electrical power for a cardiac pacemaker. In the design of the device, a capacitor can also be used to accumulate the electric charge necessary for the operation of a cardiac pacemaker, and a voltage stabilizer of the thermoelectric micromodule to the level of 1.5-2 V.

The main advantage of cardiac pacemakers with thermoelectric microgenerators is the ability to work for 30-50 years, which significantly reduces the number of medical procedures required to replace implants during the patient's life, and this, in turn, reduces the likelihood of possible complications and costs. The lifetime of such pacemakers is 5 times longer compared to the most common pacemakers with an electrochemical galvanic battery. At the same time, the negative influence of radioactive radiation inherent in pacemakers with a radioisotope thermoelectric generator is completely absent.

Comparative analysis of power supplies for cardiac pacemakers

Table 8

Comparative analysis of power supplies for cardiac pacemakers

Parameter	Electrochemical galvanic battery for single-, two- and three-chamber cardiac pacemakers	Electrochemical galvanic battery for intracardiac pacemakers	RITEG	Piezoelectric generator	Winding mechanism for cardiac pacemakers	Thermoelectric microgenerator
Mass	20-30 g	2-5 g	20-50 g	10-14 g	12 g	2-5 g
Operating voltage	1.5-2.8 V	1.5-2.0 V	4-4.7 V	1.5-2 V	~3 V	1.5-2 V
Electric power	25 mW	0.070 mW	370 mW	7 mW	0.082-0.09 mW	0.1 mW
Battery capacity	2000 mA	140 mA	–	–	–	–
Service life	8-10 years	15 years	≥30 years	≥30 years	≥30 years	≥30-50 years
Dimensions	49 × 46 × 6 mm	Ø6x42 mm	30 × 60 × 40 mm	20 × 20 × 10^{-4} mm	27 mm - 8.3 mm	5-20 mm
Toxicity	Yes	Yes	Yes	No	No	No
The degree of readiness for use	Serial production	Serial production	Out of production	Under development	Under development	Under development

From the comparative analysis it follows that the use of thermoelectric sources of electric energy for powering cardiac pacemakers holds much promise. Such sources are not toxic, have almost unlimited service life and, therefore, do not require replacement or charging. It is estimated that they can be much cheaper that chemical sources, and in terms of usage and principle of operation they are more reliable than other sources of electric energy.

Conclusions

1. A comparative analysis of the structures, the principle of operation and technical specifications of lithium-ion, radioisotope, piezoelectric, mechanical and thermoelectric power supplies for cardiac pacemakers is performed. From a comparative analysis it follows that the use of thermoelectric sources of electric energy for powering cardiac pacemakers holds much promise. Such sources are not toxic, have almost unlimited service life and, therefore, do not require replacement or charging. It is estimated that they can be much cheaper than chemical sources, and in terms of usage and principle of operation they are more reliable than other sources of electric energy.
2. It has been found that thermoelectric microgenerators implanted in the human body make it possible to generate 1.5-2 volts of electrical voltage and 100 μW of electrical power at a temperature difference of 1 °C, which is quite sufficient for powering modern pacemakers.

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ПРО ВИКОРИСТАННЯ ТЕРМОЕЛЕКТРИЧНИХ МІКРОГЕНЕРАТОРІВ ДЛЯ ЖИВЛЕННЯ ЕЛЕКТРОКАРДІОСТИМУЛЯТОРІВ

У роботі наведено конструкцію та принцип роботи сучасних електрокардіостимуляторів, а також їх класифікацію за механізмом роботи та джерелами живлення. Наведено порівняльний аналіз джерел живлення та визначено перспективи застосування термоелектричних мікрогенераторів для живлення електрокардіостимуляторів. Бібл. 66, рис.15 , табл. 8.

Ключові слова: електрокардіостимулятор, джерело живлення, термоелектричний мікрогенератор, серцево-судинні захворювання.

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ОБ ИСПОЛЬЗОВАНИИ ТЕРМОЭЛЕКТРИЧЕСКИХ МИКРОГЕНЕРАТОРОВ ДЛЯ ПИТАНИЯ ЭЛЕКТРОКАРДИОСТИМУЛЯТОРОВ

В работе описаны конструкции и принципы работы современных электрокардиостимуляторов, а также их классификация по механизму действия и источникам питания. Приведен сравнительный анализ источников питания и определены перспективы использования термоэлектрических микрогенераторов для питания электрокардиостимуляторов. Библ. 66, рис.15 , табл. 8.

Ключевые слова: электрокардиостимулятор, источник питания, термоэлектрический микрогенератор, болезни кровообращения.

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