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COMPARATIVE ANALYSIS OD THERMOELECTRIC ENERGY CONVERTERS WITH PERMEABLE AND SOLID THERMOELEMENTS

The paper describes methods for calculating the optimal parameters of two models of a thermoelectric converter in the mode of electrical energy generation, namely, a sectional converter with the heat carrier movement along the heat-absorbing junctions of thermoelements and a converter of permeable thermoelements, in which the heat carrier passes through channels located along the height of the thermoelement legs. The energy and economic indicators of such models are calculated and their comparative analysis is carried out. Bibl. 32, Fig. 10, Table. 1.
Key words: sectional thermoelectric converter, permeable thermoelement, permeable thermoelectric converter, thermoelectric generator

Introduction

In the modern world, two thirds of the thermal energy obtained from fuel combustion is not used, but released into the environment [1,2]. Only with the exhaust gases of vehicles 30 - 35% of heat is lost, which makes it impossible to save resources and preserve the environment. Thermal waste generated in technological processes, during the incineration of waste, during the operation of turbines, internal combustion engines and other heat engines can be utilized and converted into electricity by direct thermoelectric energy conversion. In [3], it was noted that about 90% of thermal waste has a temperature of up to 300 °C. This determines the relevance of the development and creation of thermoelectric generators (TEG), designed for this temperature level.

Compared to mechanical and other heat recovery technologies, thermoelectric generators have a number of undeniable advantages, such as compactness, quiet operation, reliability, durability and environmental friendliness. TEGs have no moving parts and do not require costly maintenance due to wear or corrosion of parts. Papers [4 – 20] describe examples of the practical application of TEG for generating electricity from waste heat from industrial furnaces [5 – 10], gas turbines [11 – 13], and internal combustion engines on vehicles [2, 14 – 20].

In the generator, thermal energy is transferred to the thermopile by the flow of the heat carrier (gas or liquid). The schematic of the thermoelectric converter (TEC) of the heat carrier energy is shown in Fig. 1a. The generators use two models of converters, which differ in the thermoelectric modules used in them. In the first model, the heat carrier is passed through a heat exchanger located in direct thermal contact with the heat-absorbing surface of classical thermoelectric modules, the thermoelements of which are made of solid materials (Fig. 1b). The heat carrier energy can be used more efficiently if additional heat exchangers and thermoelectric modules operating at lower temperatures are used. For this option, the thermopile consists of several sections of modules located in the direction of the heat carrier movement. The temperature of the heat exchanger base, and, hence, of the heat-absorbing junctions of thermoelements of each subsequent section will be lower than the previous one. In [3, 21], it was shown that the TEC model with several sections is more efficient than a single-section one and allows increasing the generated electric power.

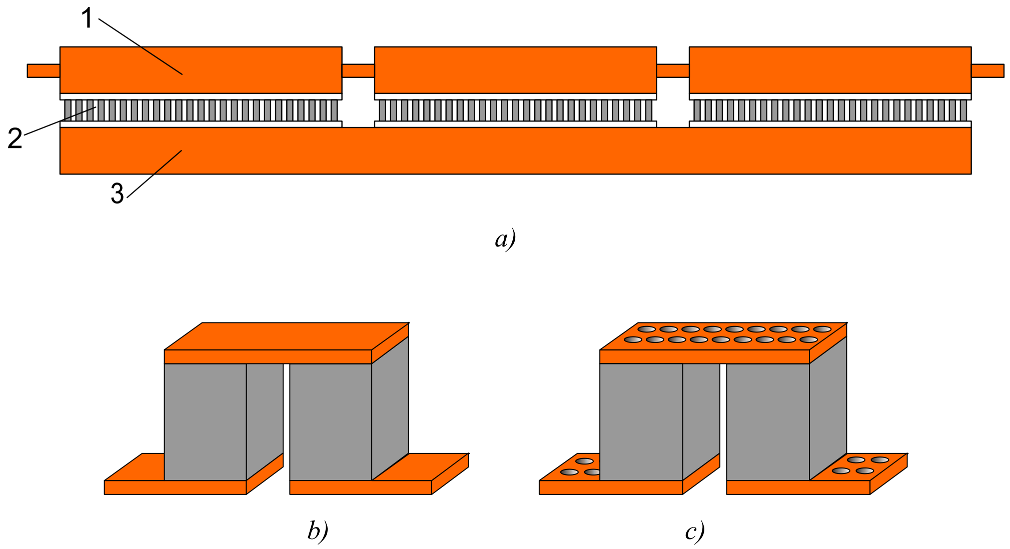

Fig. 1. a) Schematic of a thermoelectric energy converter. 1 – heat exchanger, 2 – thermoelectric module, 3 – thermostat; b) thermoelement of solid materials; c) permeable thermoelement.

In the second TEC model, modules of permeable thermoelements (Fig.1c) are used, which have pores or channels, located along the height of the legs along which the heat carrier moves. Heat transfer takes place not only in the area of junctions, but also in the bulk of thermoelectric legs. For the first time a method of increasing the efficiency of thermoelectric energy conversion using permeable thermoelements was described in the patent [22]. In [1, 23 – 27], it is proposed to use porous structures for such thermoelements. The theoretical analysis carried out in [1] showed that porous thermoelements, in comparison with solid ones, significantly improve the parameters of the generator. From the conclusions of theoretical studies of the indicators of channel permeable TEC, carried out in [28 – 30] by methods of optimal control theory, it follows that their efficiency increases by a factor of 1.2 – 1.4 compared to classical modules made of solid materials.

Hence, a question arises as to which of the TEC models, sectional or permeable, is more rational. Therefore, the purpose of this work was to carry out a comparative analysis of the energy and economic indicators of the sectional and permeable TEC and to establish which of the models is more effective for practical use, in particular in systems for utilizing thermal waste.

Method of calculating the parameters of sectional TEC

The schematic of sectional TEC is shown in Fig. 2. In the general case, the TEC contains N sections located along the direction of the heat carrier flow. Each section consists of a heat exchanger through which the heat carrier moves, classical thermoelectric modules made of thermoelements of solid materials. We assume that the temperature T0 of the heat-generating surfaces of thermoelectric modules is kept constant.

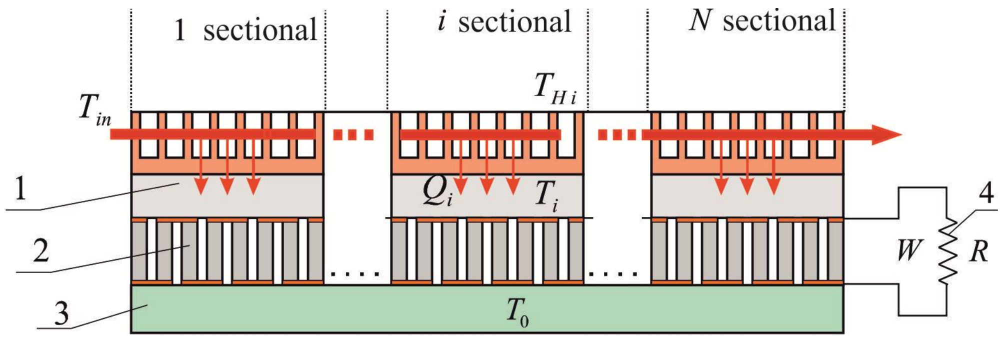

Fig. 2. Schematic of N-sectional TEC. 1 – heat exchanger, 2 – thermoelectric modules, 3 – thermostat, 4 – matched electric load.

The task is to evaluate the optimal parameters of each section, which ensure the maximum efficiency of the TEC in the generator mode at a given temperature T_{in} of the heat carrier at the inlet to the heat exchanger and the mass flow rate m of the heat carrier.

The efficiency of TEC is determined as follows:

$$\eta = \frac{W}{G(T_{in} - T_0)} , \tag{1}$$

where $G = c_p m$ is total heat capacity of the heat carrier, c_p is its specific heat, W is total power generated by TEC. Taking into account that, according to the conditions of the problem, T_0 and T_{in} are given, the maximum value of η corresponds to the maximum power W:

$$W = \sum_{i=1}^{N} W_i , \tag{2}$$

where W_i is the power of the i-th section of TEC.

The following approximations are used to solve the problem.

1. In the steady state, the temperature of the heat exchanger base of the i-th section does not depend on the coordinates and is equal to the temperature T_i of the heat-absorbing surface of the modules of the i-th section.

2. Stirring in the flow of heat carrier is quite intense and the average temperature of the heat carrier at the outlet of the i-th heat exchanger is equal to the temperature of the heat carrier at the inlet to the $(i + 1)$-th heat exchanger, i.e.

$$T_{in\, i+1} = T_{H\, i} . \tag{3}$$

3. The Seebeck coefficient α, the resistivity ρ and the thermal conductivity κ are temperature independent and have the same value for *n*- and *p*-type legs.

4. The heat transfer coefficient α_T of the heat carrier and its heat capacity c_p are temperature independent.

5. Heat loss to the environment is neglected.

According to these assumptions, the power of the heat transferred by the heat carrier of the *i*-th section is determined as follows

$$Q_i = G(T_{in\,i} - T_{H\,i}) \tag{4}$$

and is equal to the thermal power of convective heat exchange with the heat carrier in the *i*-th heat exchanger, i.e.

$$Q_i = \alpha_T K S_{TE\,i}(T_{H\,i} - T_i)\,, \tag{5}$$

where $K = S_{H\,i}/S_{TE\,i}$ is the ratio between the area of the heat exchanger base $S_{H\,i}$ and the total cross-sectional area $S_{TE\,i}$ of thermoelement legs in the *i*-th section.

The electric power generated by the thermopile of the *i*-th section is determined from the ratio

$$W_i = \eta_i(T_i, T_0)Q_i = \eta_i(T_i, T_0)G(T_{H\,i-1} - T_{H\,i})\,, \tag{6}$$

which takes into account condition (3) and notation $T_{H\,0} = T_{in}$. In this expression, $\eta_i(T_i, T_0)$ is the maximum value of the efficiency of the thermopile of the *i*-th section, determined by formula [31]

$$\eta_i(T_i, T_0) = \frac{T_i - T_0}{T_i}\frac{M-1}{M + T_0/T_i}\,, \tag{7}$$

where $M = \sqrt{1 + 0.5Z(T_i + T_0)}$, $Z = \dfrac{\alpha^2}{\rho\kappa}$. The heat balance condition is fulfilled on the heat-absorbing surface of the *i*-th thermopile, namely

$$Q_i = Q_{h\,i}\,, \tag{8}$$

where $Q_{h\,i}$ is the heating capacity of the *i*-th thermopile, which in the maximum efficiency mode satisfies the relation [31]

$$Q_{h\,i}(T_i, T_0) = \frac{\kappa S_{TE\,i}}{L}\frac{ZM(T_iM + T_0)(T_i - T_0)}{(M+1)^2(M-1)}\,, \tag{9}$$

where *L* is the height of thermoelement legs. Then, from the heat balance condition (8), the expression for the heat carrier temperature $T_{H\,i}$ is obtained:

$$T_{H\,i} = T_i + \frac{\kappa}{\alpha_T K L}\frac{ZM(T_iM + T_0)(T_i - T_0)}{(M+1)^2(M-1)}\,. \tag{10}$$

Using expressions (6), (7), (10), by formula (2) the total power of TEC is determined as a function of temperatures of heat-absorbing junctions of thermoelements of all sections: $W = W(T_1, ..., T_N)$. Computer methods are used to find the optimal sequence of the temperatures of the junctions T_i and, accordingly, the temperatures of the heat carrier T_{Hi} in the heat exchangers, at which the power W, and hence the efficiency of the TEC, acquire maximum values.

Subsequently, for optimal temperature distributions T_i and T_{Hi} the power values of each section W_i ((6) are found, and from the ratio

$$\rho \frac{L}{S_{TEi}} = \frac{\alpha^2 (T_i - T_0)^2}{4W_i} \tag{11}$$

the total cross-sectional area S_{TEi} of the thermoelement legs of each section is calculated under conditions of a given leg height L. The volume of thermoelectric material is determined by the formula $V = L\sum_{i=1}^{N} S_{TEi}$.

Method of calculating the parameters of a permeable TEC

The permeable TEC is formed by series-connected permeable modules of thermoelements with channels in the connecting plates and legs directed along the height of the legs. The model of a permeable thermoelement is shown in Fig. 3.

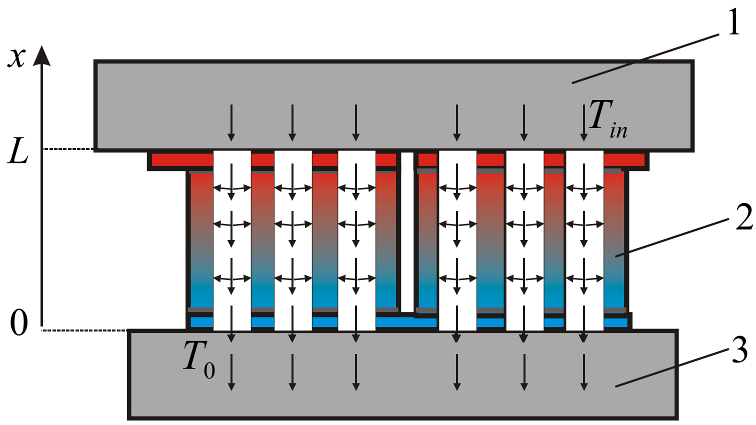

Fig. 3. Model of a permeable thermoelement. 1 – heat carrier container, 2 – thermoelement with channels for heat carrier, 3 – thermostat

As with the previous model of sectional TEC, we assume that the parameters of thermoelectric materials are temperature independent and their value is the same for n- and p-legs. The lateral surfaces of the legs are adiabatically isolated. The temperature T_0 of the heat-generating junctions of permeable thermoelements is kept constant. The heat carrier moves along the channels, gives off heat to the volume of thermoelement legs and cools down.

Similar to the sectional TEC, the task is to find the optimal parameters of the permeable TEC that provide the maximum efficiency at a given temperature T_{in} of the heat carrier at the inlet to the channels and the heat carrier flow rate m. The efficiency of a TEC is characterized by the efficiency of its individual permeable thermoelement, determined by the formula

$$\eta = \frac{W_{TE}}{c_p m_{TE} (T_{in} - T_0)} , \tag{12}$$

where m_{TE} is heat carrier flow rate for thermoelement, W_{TE} is power generated by thermoelement.

To calculate the efficiency, it is necessary to solve a stationary boundary-value problem describing the temperature and heat flux distributions in the thermoelement legs and the heat carrier flow. In the one-dimensional approximation, the system of differential equations of this problem has the form [30]

$$\begin{aligned} \frac{dT}{dx} &= -\frac{\alpha j}{\kappa}T - \frac{j}{\kappa}q, \\ \frac{dq}{dx} &= \frac{\alpha^2 j}{\kappa}T + \frac{\alpha j}{\kappa}q + j\rho + \frac{\alpha_e}{jS}(t-T), \\ \frac{dt}{dx} &= \frac{\alpha_e}{c_p m_{TE}}(t-T), \end{aligned} \quad (13)$$

where the following notation is used: T is temperature of the thermoelement, t is temperature of the heat carrier in the channels, $q = \frac{1}{j}\left(\alpha jT - \kappa\frac{dT}{dx}\right)$ is specific heat flux in the thermoelement legs, S is cross-sectional area of the thermoelement leg material, $j = I/S$ is current density in the thermoelement legs, $\alpha_e = \alpha_T P_c N_c$, $\square_T$ is heat transfer coefficient in the channels, N_c is the number of channels in the thermoelement legs, P_c is the perimeter of the channel.

The boundary conditions of the problem for the system of equations (13):

$$T(0) = T_0, \quad t(L) = T_{in}, \quad q(L) = 0. \quad (14)$$

The electric power generated by the permeable thermoelement is calculated by the formula

$$W_{TE} = Q_h - Q_0, \quad (15)$$

where $Q_h = c_p m_{TE}\left(T_{in} - t(0)\right)$ is power of heat absorbed in the channels of permeable thermoelement, $Q_0 = q(0)jS$ is the heat given off by the heat-releasing thermoelement surface to the environment.

Therefore, according to expressions (12) and (15), the maximum efficiency of permeable TEC under conditions of determined geometry and size of thermoelements is achieved if the heat carrier flow rate m_{TE} in the channels and current densities j in the thermoelement legs take optimal values. The optimization problem lies in finding the maximum efficiency (12) of the permeable thermoelement, under the conditions of constraints imposed on the thermoelement by the boundary value problem (13) – (14). This problem is solved by the methods of optimal control theory using the Pontryagin maximum principle [32]. Optimality conditions and examples of solving such a problem are given in [29, 30]. The problem is solved with the help of computer tools.

The results of solving the problem are the optimal values of the electrical power W_{TE} and the heat carrier flow rate m_{TE} for the thermoelement, which ensure maximum efficiency. The number of series-connected thermoelements N_{TE} in the generator thermopile to ensure the specified heat carrier consumption *m*, the total power *W* and the volume of the thermoelectric material *V* are calculated by the formulae

$$N_{TE} = m/m_{TE}, \quad W = W_{TE}N_{TE}, \quad V = N_{TE}LS. \quad (16)$$

Thus, the methods for calculating and optimizing the parameters of the sectional and permeable TEC are fundamentally different. The sectional model requires optimization of the generator thermopile as a whole, and in the permeable model it is sufficient to optimize the parameters of a separate thermoelement.

This feature is explained by the fact that due to the difference in the flow patterns of the heat carrier in these TEC models, solid thermoelements in different sections operate in different temperature conditions, and permeable thermoelements - in the same. Accordingly, there is a need for a correct comparison of the theoretical results of optimization of the sectional and permeable TEC in order to identify a more rational model of the converter for its further practical implementation.

Results of calculating the parameters of sectional and permeable TEC and their comparison

To compare two TEC models made of Bi_2Te_3-based materials, the maximum efficiency, the generated power and the corresponding values of thermoelectric material consumption and its unit cost were calculated. The calculations were carried out at the same for both models given values of the heat carrier flow rate and its temperature at the inlet to the TEP heat exchanger. The initial data for the calculation are presented in Table 1.

TEC indicators depend on the intensity of heat transfer, characterized by the heat transfer coefficient α_T and the heat transfer area. The coefficient α_T was chosen the same for both TEC models. As for the heat exchange area, for the sectional model it depends on the ratio between the area of the heat exchanger base and the total cross-sectional area of thermoelectric legs in the sections, characterized by the coefficient K. For a permeable TEC, the heat exchange area depends on the number of channels of a given diameter located on an area S = 1 cm^2 of the thermoelectric material. Therefore, for calculating the optimal TEC indicators, the heat exchange area cannot be a predetermined value. Therefore, the parameters of the sectional TEC were calculated for two options, namely, for the rational case of heat exchange with the coefficient K = 3.5 and for the “ideal” case when the temperature of the heat-absorbing junctions of thermoelements is considered equal to the temperature of the heat carrier in the heat exchanger, i.e. heat transfer does not affect the TEC parameters. For the permeable converter model, the calculations were performed for the TEC with a different number of channels.

Table 1

Values of quantities used to calculated TEC parameters

Quantity	Value
Seebeck coefficient □, μV/K	230
Resistivity □, Ohm□cm	1.25□10^{-3}
Thermal conductivity □, W/cm□K	0.015
Coefficient of heat exchange □$_T$, W/ cm^2□K	0.015
Specific heat of heat carrier (gas CO_2) c_p, J/(g□K)	1000
Heat carrier flow rate m, g/s	1.15□10^{-3}
Heat carrier temperature at the inlet to heat exchanger T_{in}, □C	100 – 300
Temperature of heat-releasing surface of TEC T_0, □C	50

The results of calculating the parameters of two TEC models are shown in Fig. 4-10. First of all, it was necessary to determine the rational number of sections for a sectional TEC and the rational height of the legs for a permeable TEC.

Fig. 4 shows the dependences of the maximum efficiency on the number of sections N of the converter and the height of the legs L of permeable thermoelements. The calculations were carried out at a heat carrier inlet temperature T_{in} = 300 °C, for a sectional TEC with a leg height of 1 cm, K = 3.5 and for a permeable TEC with 25 channels per 1 cm^2 of material area. With an increase in the number of sections or the height of the permeable legs, the efficiency for both TEC models grows and tends to the same value, in this case up to η_{max} = 4 %. This is due to the increase in the area of heat transfer, which allows more complete use of the thermal power of the heat carrier, which for both models in this case is $Q_{heat} = c_p m(T_{in} - T_0) = 287.5$ W. For a sectional TEC, it is advisable to use 3 – 4 sections, and for a permeable TEC, the height of legs up to 2 cm is rational. It is clear that a further increase in the number of sections or height does not significantly increase the efficiency, but drastically increases the thermoelectric material consumption.

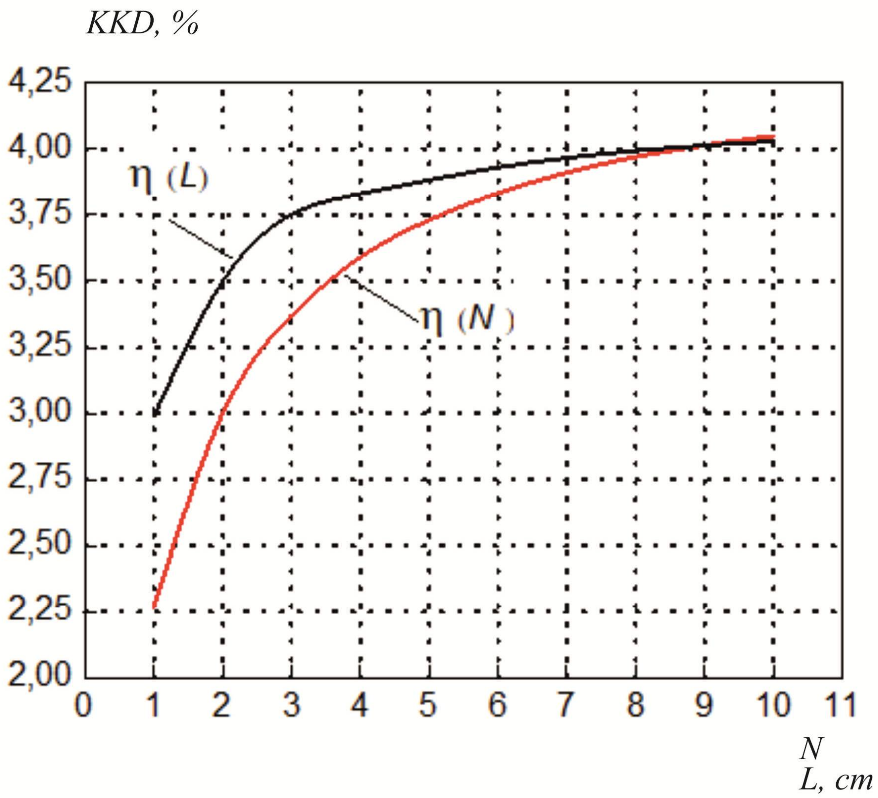

Fig. 4. η(N) – the efficiency of sectional TEC versus the number of sections N. η(L) – the efficiency of permeable TEC versus the height L of thermoelement legs.

Fig. 5 shows the dependence of the efficiency of a sectional TEC with a different number of sections on temperature T_{in} of the heat carrier at the inlet to the heat exchanger. The calculations were made taking into account the heat transfer between the heat carrier and the heat-absorbing surface of the TEC (solid lines) and for the "ideal" case in the approximation when heat transfer is not taken into account (dashed lines), that is, the heat transfer coefficient $\alpha_T \to \infty$.

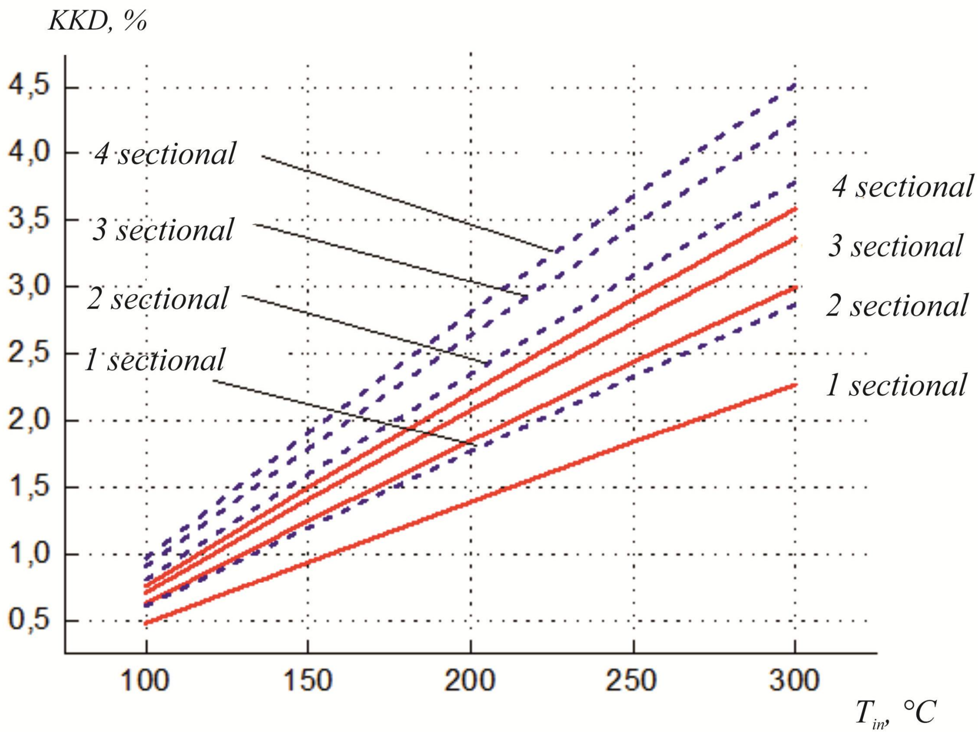

Fig. 5. The efficiency of sectional TEC with regard to heat exchange (solid lines) and without heat exchange (dashed lines). The height of thermoelement legs is 1 cm.

The efficiency depends on the number of sections. These results emphasize the conclusion that the most rational model is a three-section TEC. A further increase in the number of sections does not lead to a significant increase in the efficiency of thermal energy conversion.

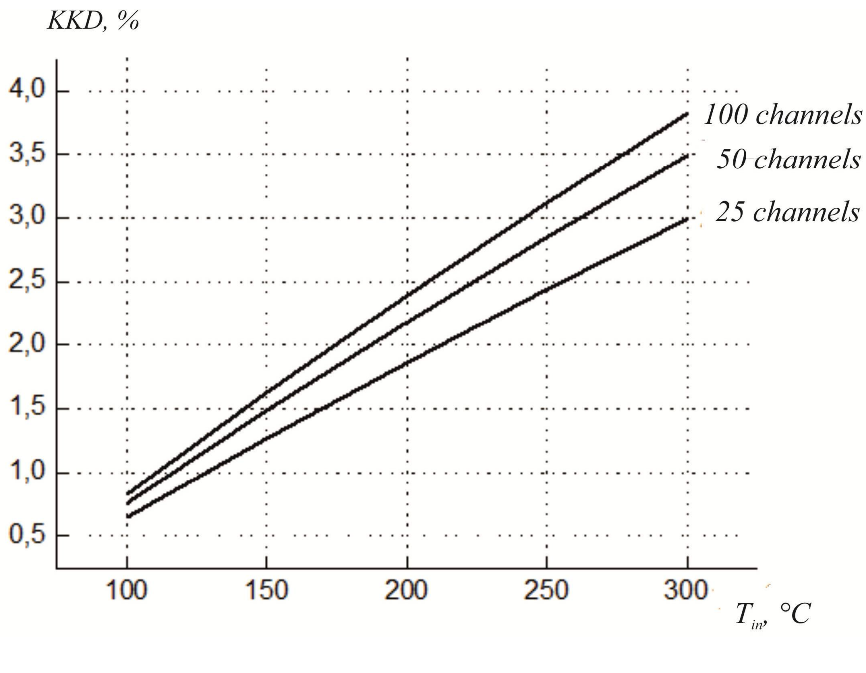

Fig. 6. The efficiency of permeable TEC with a different number of channels on 1 cm^2 of thermoelectric material area.

Fig. 6 shows the dependence of the efficiency on the temperature T_{in} of the heat carrier at the inlet to a permeable TEC with a leg height of 1 cm and a different number of channels per 1 cm^2 of the thermoelectric material area (channel diameter 1 mm). From comparison of these results with the data for the permeable TEC in Fig. 6 it follows that for T_{in} = 300 °C the efficiency of permeable thermoelements 1 cm high with 50 channels and 2 cm high with 25 channels are practically the same. Consequently, in a permeable TEC, it is advisable to increase the area of heat exchange with the heat carrier by increasing the number of channels, rather than increasing the height of the legs, because this will not lead to an increase in the volume of the thermoelectric material.

For comparison, Fig. 7 shows the dependence of the efficiency of the heat carrier temperature at the inlet to the heat exchanger for sectional (solid lines) and permeable (dashed lines) TEC. The efficiency values of the most rational TEC designs, namely a three-section TEC and a permeable TEC with 50 channels per 1 cm^2, do not differ significantly. At a heat carrier temperature T_{in} =300 °C, the efficiency of these TEC options reaches 3.5%.

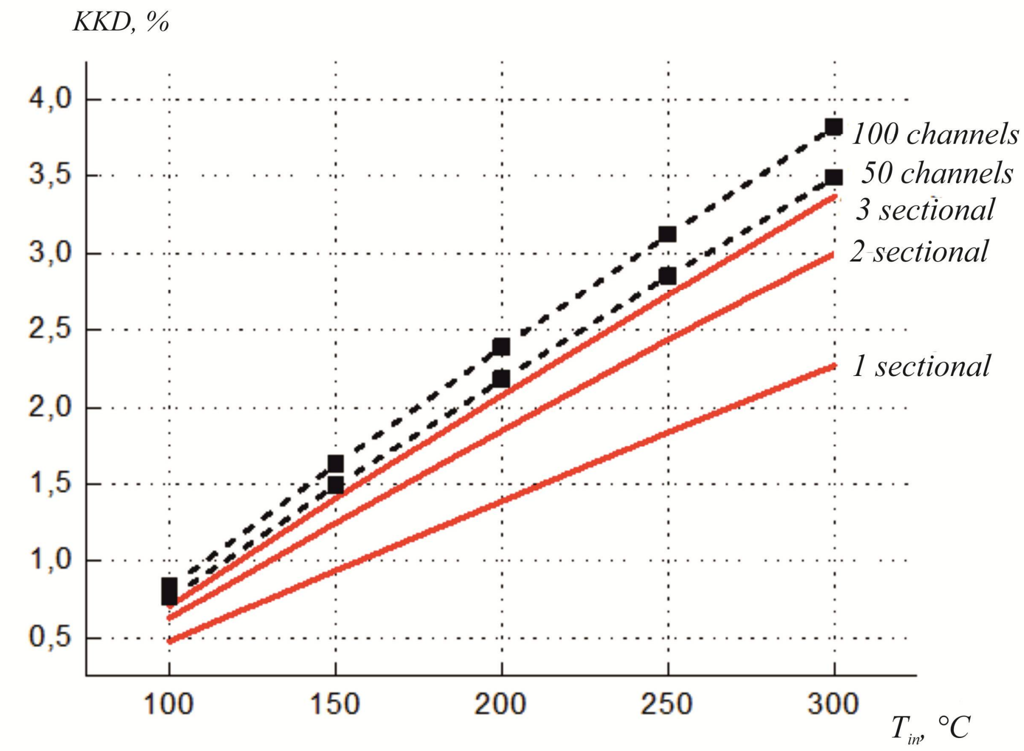

Fig. 7. Comparison of the efficiency of sectional and permeable TEC.

The efficiency of permeable TEC increases if you increase the number of channels for the heat carrier. Under these conditions, the area of heat exchange between the heat carrier and the thermoelectric material is enlarged, which increases the efficiency. The rational number of channels is from 50 to 100. Further increase in the number of channels does not significantly increase the efficiency.

To increase the efficiency of sectional TEC, it is advisable to improve the heat transfer system between the heat carrier and the hot surface of the thermopile in order to improve the convective heat transfer between the heat carrier and the heat exchanger. Under these conditions, the efficiency increases and approaches the value of the efficiency in the ideal case when heat transfer does not affect the efficiency (Fig. 5).

Fig. 8 shows the results of calculating the maximum electrical power for different designs of TEC. At a heat carrier temperature of 300 °C, the power of a 3-section TEC and a permeable TEC with 50 channels per 1 cm^2 is about 10 W.

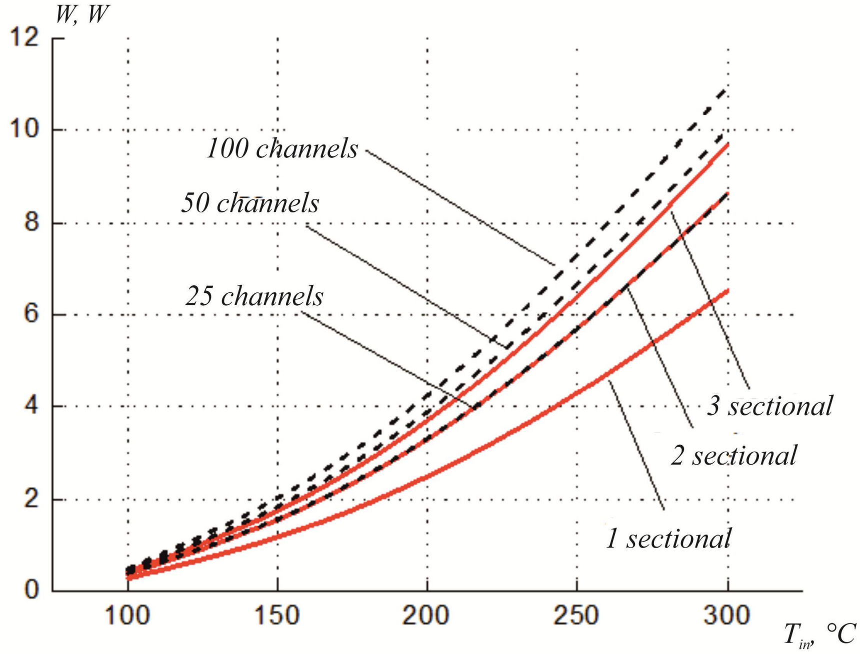

Fig. 8. Maximum electric power of sectional and permeable TEC.

To compare the economic performance of the two TEC models, the volume of thermoelectric material, its consumption and the unit cost of obtaining 1 W of electricity were calculated. The results are shown in Fig. 9, 10.

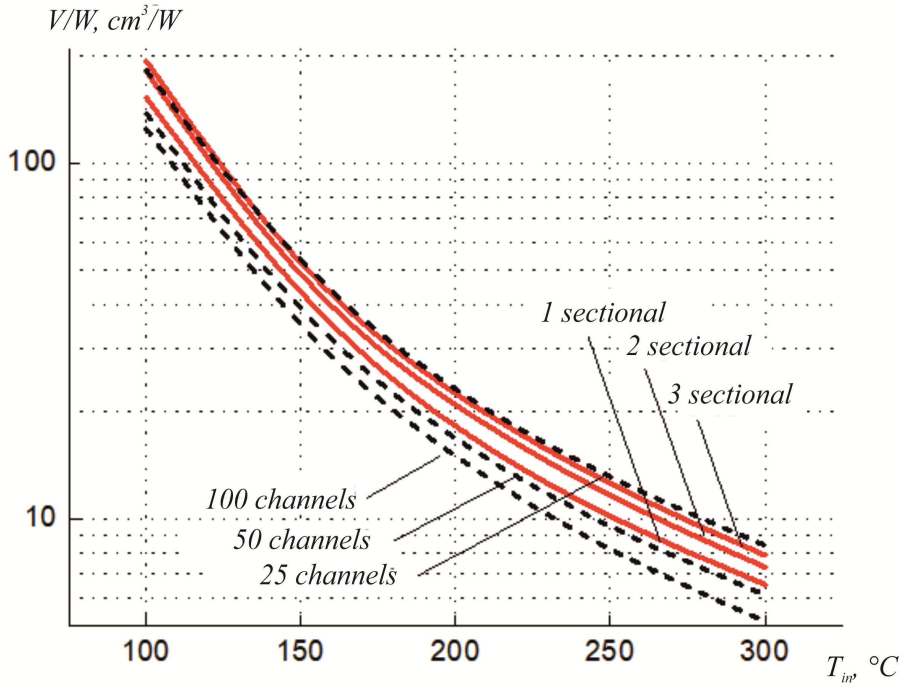

Fig. 9. Consumption of thermoelectric material for sectional and permeable TEC per 1 W of generated electric energy.

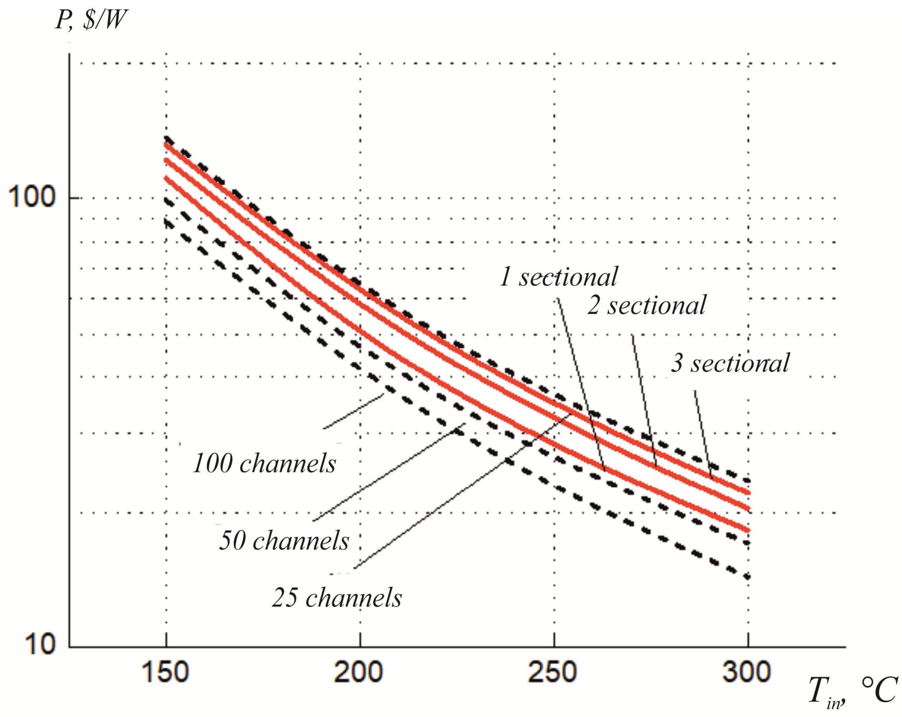

Fig. 10. Unit cost of material for sectional and permeable TEC.

According to these parameters, a permeable TEC which has from 50 to 100 channels per 1 $см^2$ in the legs of thermoelements is more efficient. Material consumption and unit cost for such a TEC is 25 - 35% less compared to a three-section converter.

Note that the economic characteristics of TEC significantly depend on the temperature of the heat carrier at the inlet to the heat exchanger. With a rise in temperature from 100 °C to 300 °C, the material consumption and the unit cost of both sectional and permeable TEC decrease by a factor of 25.

Conclusions

The calculation and comparison of the parameters of sectional and permeable TEC allow the following conclusions:

1. In the ideal case, when the heat exchange area between the heat carrier and the thermoelectric material increases infinitely, the efficiency of a sectional thermoelement made of classical thermoelements of solid materials and a converter made of permeable thermoelements will be the same.

2. The most rational real models are a 3-section TEC of classical thermoelements and a permeable TEC, which has 50 channels per 1 cm^2 of thermoelectric material. The efficiency of these TECs is not much different.

3. In terms of economic indicators, a TEC made of permeable thermoelements is a better model, for which the consumption of thermoelectric material and the unit cost of 1 W of electricity can be 25 - 35% less than that of a sectional TEC.

4. Further research is needed on the effect of an increase in the heat exchange area in permeable modules and a decrease in the height of the legs of thermoelements made of solid materials in classical modules for each section on the energy and economic indicators of TEC.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ ТЕРМОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ ЕНЕРГІЇ З ПРОНИКНИМИ ТА

УЦІЛЬНИМИ ТЕРМОЕЛЕМЕНТАМИ

В роботі описані методи розрахунку оптимальних параметрів двох моделей термоелектричного перетворювача в режимі генерації електричної енергії, а саме секційного перетворювача з рухом теплоносія вздовж теплопоглинальних спаїв термоелементів і перетворювача з проникних термоелементів, в якому теплоносій проходить по каналам, розташованим вздовж висоти віток термоелементів. Розраховані енергетичні та економічні показники таких моделей і проведено їх порівняльний аналіз. Бібл. 32, рис. 10, табл. 1.

Ключові слова: секційний термоелектричний перетворювач, проникний термоелемент, проникний термоелектричний перетворювач, термоелектричний генератор

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ ТЕРМОЭЛЕКТРИЧЕСКИХ ПРЕОБРАЗОВАТЕЛЕЙ ЭНЕРГИИ С ПРОНИЦАЕМЫМИ И СПЛОШНЫМИ ТЕРМОЭЛЕМЕНТАМИ

В работе описаны методы расчета оптимальных параметров двух моделей термоэлектрического преобразователя в режиме генерации электрической энергии, а именно секционного преобразователя с движением теплоносителя вдоль теплопоглощающих спаев термоэлементов и преобразователя из проницаемых термоэлементов, в котором теплоноситель проходит по каналам, расположенным вдоль высоты. Рассчитаны энергетические и экономические показатели таких моделей и проведен их сравнительный анализ. Библ. 32, рис. 10, табл. 1.

Ключевые слова: секционный термоэлектрический преобразователь, проницаемый термоэлемент, проницаемый термоэлектрический преобразователь, термоэлектрический генератор

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