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Optimization of the Efficiency of Permeable Thermoelectric Elements for Air Conditioner Applications

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The optimization of permeable thermoelement for thermoelectric air conditioner unit based is presented. In the thermoelectric air conditioner unit the air flow is cooled due to a combined action of thermoelectric effects and the Joule-Thomson effect. Methods for calculation of temperature distribution, determination of power conversion energy characteristics and thermoelement design in maximum COP mode are discussed. Results of computer studies for the case of thermoelement legs based on Bi_2Te_3 material have shown the possibility of COP increase by a factor of 1.6 - 1.7 as compared to conventional thermoelectric systems.

Keywords: thermoelectricity, thermoelements, bismuth telluride, coefficient of performance, air conditioner.

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Introduction

Thermoelectric cooling systems are environmentally friendly (freon-free), noise-free, noteworthy for simple design, high reliability, random attitude in space, possibility of stepless and precise control of cooling capacity and temperature, which shows their good prospects for creation of air conditioning thermal modes. However, despite such attractive characteristics, thermoelectric cooling systems have not found wide application in solving the problems of air thermal stabilization, which is due to their lower coefficient of performance values as compared to compressor devices. Therefore, efficiency increase of thermoelectric air conditioning systems is a topical problem.

Possibilities of wide application of thermoelectric cooling are primarily dependent on their energy efficiency, i.e. coefficient of performance (COP). Creation of thermoelectric materials with maximum figure of merit, use of cascade structures and improvement of heat exchange system are considered to be the main lines of COP increase in thermoelectricity.

Methods for improving the figure of merit of thermoelectric materials were stated by A.F. Ioffe as early as the mid twentieth century [1]. They consist in doping substrate material with active impurities to achieve maximum $\alpha^2\sigma$ values and doping material with isovalent substitution impurities to reduce thermal conductivity. These methods were applied to some materials which improved the figure of merit and, respectively, contributed to a wide practical use of thermoelectricity. However, in recent decades, despite numerous studies, further increase in the figure of merit of thermoelectric materials has been minor. New ways of efficiency improvement should be sought for. Therefore, increasing attention is paid to investigation of alternative lines – the one-dimensional and whisker quantum structures, film materials and quantum well composites. Research is also made on thermoelectric materials with programmable inhomogeneity (FGM) helping to improve energy efficiency due to the use of the bulk thermoelectric effects and proper account of temperature dependence of material properties [2, 3]. The use of cascade structures [3, 4] enables COP increase by 30 - 60 %.

Consider now the possibilities of heat exchange system improvement. Intensification of heat exchange system allows reducing temperature difference on thermoelement, and system COP is thereby increased. This approach can be realized by means of thermal pipes and thermosyphons. It is shown [4] that using of thermosyphons for standard thermoelectric modules 40×40 mm allows increasing system COP by 30 %.

In terms of system COP increase, it is also appealing to use closed cycles of heat carrier motion in the heat exchange systems of the cold and hot thermopile surfaces. With good heat exchange intensity, such approach makes it possible to reduce temperature differences on thermoelements and maintain the necessary cooling of heat carrier in the thermopile. In the multi-element thermoelectric systems [5, 6] it allows improving system COP by 40 - 60 %.

The most efficient are heat exchange systems wherein heat input or removal is not only through the surfaces of the hot and cold junctions, but also through the internal surfaces of thermoelement legs. Such thermoelements are commonly called permeable or thermoelements with a developed internal heat exchange [7-9].

In permeable thermoelements pumping of heat carrier through channels (pores) of material can cause its additional cooling due to the Joule-Thomson effect created at throttling of gas flows [11]. This can help to realize such situations when a combined action of thermoelectric effects and the Joule-Thomson effect will enable COP increase. Air coolers show good promise for practical implementation since there is growing demand for thermoelectric air conditioners for small rooms, means of mobile and electron communication, etc.

Therefore, the purpose of this paper is to establish the possibilities of improving the energy efficiency of thermoelectric air conditioner with a combined action of thermoelectric effects and the Joule-Thomson effect.

I. Physical model and mathematical description of the problem

Fig. 1 shows a schematic of thermostating unit of thermoelectric air conditioner based on permeable thermoelements [12]. Air flow 1, for thermostating, is fed by fan 2 along pipe 4 through purification filter 11 and hot heat exchanger 5 to the unit of permeable thermoelements 3.

The electric current of required polarity passed through the thermoelements results in cooing their lower sides. Air passing through channels of thermoelements toward the cold junctions is also cooled due to heat exchange with materials of the legs, and cooled air 14 is fed through pipe 13 to the consumer. Heat from the “hot” sides of thermoelements is removed by heat exchanger 5 by means of heat carrier that circulates in pipe 6 and discharges heat to the environment. Pipe 8 and damper 7 with fan 9 serve for air intake from the environment. The basic component of the unit is a thermopile of permeable thermoelements 3 the characteristics of which define power efficiency of device.

Permeable thermoelements 3 are based on *p*- and *n*-type thermoelectric material including channels (pores) for pumping of gas heat carrier to be cooled. Thermal load on thermoelement from the gas flow being cooled is created due to heat exchange inside the thermoelement legs. The hot and cold thermoelement sides are maintained at constant T_h and T_c values, respectively. Heat carrier is pumped from the hot to cold junctions.

Passing of the electric current of required polarity results in the origination of known thermoelectric effects with cooling of the upper and heating of the lower parts of the legs. Heat carrier being pumped through the channels (pores) in thermoelement legs in the direction from the hot to cold junctions, due to heat exchange with

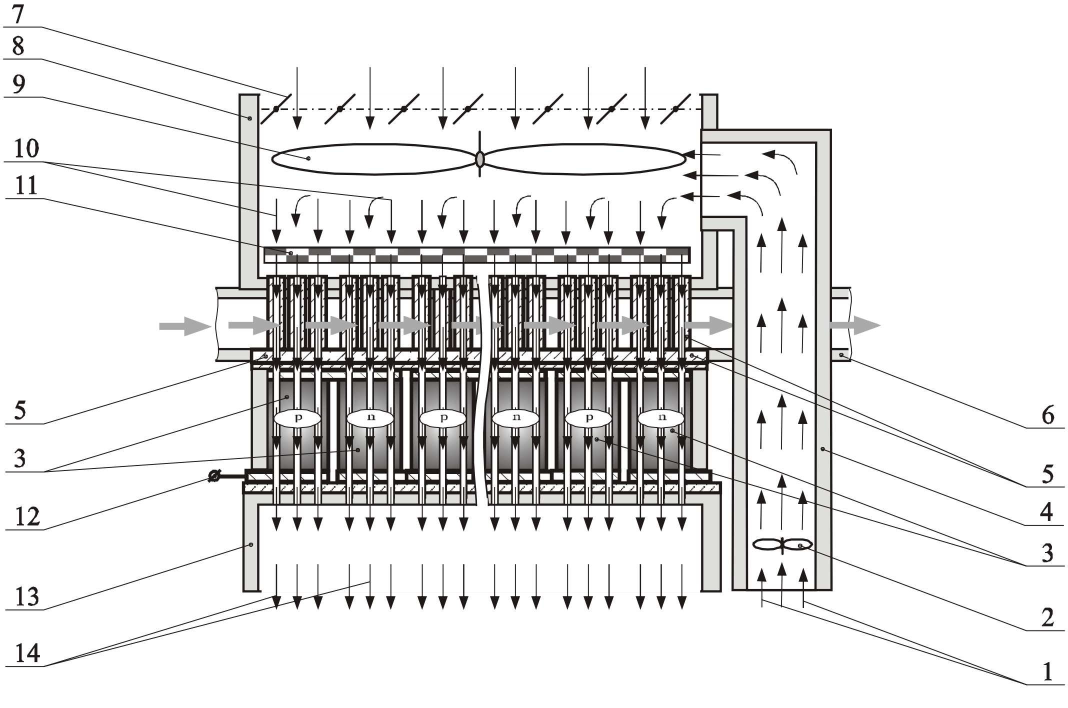

Fig. 1. The thermostatic unit of thermoelectric air-conditioner.

the bulk of the legs material is also cooled. Additional action of the Joule-Thomson effect described by the relationship [13] in the form:

$$dt = \mu_{JT}\,dp\,, \qquad (1)$$

causes more intensive cooling of heat carrier passing through the legs.

To formulate the problem on determination of temperature fields, the energy characteristics of power conversion and design of such power converters, let us consider physical model of cooling thermoelement using the Joule-Thomson effect.

Physical model of cooling permeable thermoelement comprises *n*- and *p*- type legs, where material properties vary with coordinate *x* due to their temperature dependence *T*(*x*). Heat from the heat carrier is transferred to thermoelement material through heat exchange with the internal surface of leg channels.

A steady-state one-dimensional temperature distribution in the legs material *T*(*x*) and in the heat carrier *t*(*x*) can be found from the solution of differential equation system [14] with account of the Joule-Thomson effect:

$$\left.\begin{aligned} &\frac{dq}{dx}=\frac{\alpha^2 j}{\kappa}T+\frac{\alpha j}{\kappa}q+j\rho-\frac{h\,\Pi_K N_K l^2}{\left(S-S_K\right)j}\left(T-t\right),\\ &\frac{dT}{dx}=-\frac{\alpha j}{\kappa}\,T-\frac{j}{\kappa}q,\\ &\frac{dt}{dx}=\frac{h\,\Pi_K N_K l}{Vc_p S_K}\left(T-t\right)-\mu_{JT}l\frac{dp}{dx}. \end{aligned}\right\}_{n,p} \qquad (2)$$

where $j = il$; $i=\dfrac{I}{S-S_K}$;

$q=\dfrac{1}{j}\left(\alpha\left(T,\xi(x)\right)jT-\kappa\left(T,\xi(x)\right)\dfrac{dT}{dx}\right)$, $x=\dfrac{x}{l}$ is dimensionless coordinate; α(*T*), κ(*T*), ρ(*T*) are thermoelectric coefficient, thermal conductivity and resistivity of material as functions of temperature *T*.

The intensity of heat exchange between the walls of channels and the heat carrier is varied along the leg height. Dependence of heat exchange coefficient h on the hydrodynamic pattern, the heat carrier flow mode and the thermophysical properties of the medium was taken into account according to relation [15]

$$h=\frac{\lambda_m\cdot 1.4\cdot(\mathrm{Re}_m\frac{d}{l})^{0.4}\cdot \mathrm{Pr}_m^{0.33}\cdot(\frac{\mathrm{Pr}_m}{\mathrm{Pr}_c})^{0.25}}{d}. \qquad (3)$$

Pressure variation $\dfrac{dp}{dx}$ in the direction of heat carrier flow is described by the Darcy-Weisbach relation:

$$\frac{dp}{dx}=\xi_d\,\frac{\pi V^2}{2\Pi_K\rho g}. \qquad (4)$$

With regard to (4), the differential equation system (2) will be written as:

$$\left.\begin{aligned} &\frac{dq}{dx}=\frac{\alpha^2 j}{\kappa}T+\frac{\alpha j}{\kappa}q+j\rho-\frac{h\,\Pi_K N_K l^2}{\left(S-S_K\right)j}\left(T-t\right),\\ &\frac{dT}{dx}=-\frac{\alpha j}{\kappa}\,T-\frac{j}{\kappa}q,\\ &\frac{dt}{dx}=\frac{h\,\Pi_K N_K l}{Vc_p S_K}\left(T-t\right)-\mu_{JT}\xi_d\frac{\pi V^2 l}{2\Pi_k\rho g}. \end{aligned}\right\}_{n,p} \qquad (5)$$

Let us consider a problem of maximum energy efficiency of thermoelectric cooling at fixed temperatures of heat sources and sinks.

The problem reduces to a search for maximum COP

$$\varepsilon=\frac{Q_c}{W}=\frac{Q_c}{Q_h-Q_c} \qquad (6)$$

at differential relations (5) and boundary conditions:

$$T_{n,p}\left(0\right)=T_h,\quad T_{n,p}\left(l\right)=T_c,\quad t_{n,p}\left(0\right)=T_a, \qquad (7)$$

where Q_h, Q_c, are heat flows exchanged between the thermoelement and the external heat sources:

$$Q_h=Q_n\left(0\right)+Q_p\left(0\right),\quad Q_c=Q_n\left(1\right)+Q_p\left(1\right)+Q_L,$$

where Q_L is heat input due to internal heat transfer from the heat carrier being cooled $Q_L=\sum\limits_{n,p}Vc_pS_K\left(t(0)-t(1)\right)$.

Hereinafter, instead of maximum ε it is convenient to consider the minimum of functional J:

$$J = \ln q(0) - \ln q(1), \qquad (8)$$

where $q(0)=\dfrac{Q_h}{I}=q_n(0)+q_p(0)$,

$$q(1)=\frac{Q_c}{I}=q_n(1)+q_p(1)+\frac{Q_L}{j\left(S-S_K\right)}l,$$

$q_n\left(1\right),q_p\left(1\right),q_n\left(0\right),q_n\left(0\right)$ are the values of specific heat flows on the cold and hot thermoelement junctions for legs of *n*- and *p*-types that are found from the solution of system (5).

The problem of optimization consists in choosing from a plurality of permissible controls $\xi\in G_\xi$ such specific mass velocity of heat carrier in channels $V=V_o$ that under restrictions (5), (7) and condition for electric current density *j*:

$$q_n(1) + q_p(1) = 0 \tag{9}$$

functional J is imparted with the lowest value, thereby COP ε will be maximum.

II. Method for solving the formulated problem

To solve the formulated problem, we shall use the Pontryagin mathematical theory of optimal control [17] as applied to thermoelectric power conversion [18]. The formalism of mathematical theory of optimal control will be specified with reference to our problem.

Let us introduce the Hamiltonian function:

$$H = \psi_1 f_1 + \psi_2 f_2 + \psi_3 f_3 \ , \tag{10}$$

where f_1, f_2, f_3 are right-hand sides of equation set (5):

$$f_1 = -\frac{\alpha \ j \ T}{\kappa} - \frac{j\, q}{\kappa}, \quad f_2 = \frac{\alpha^2 j}{\kappa} T + \frac{\alpha \ j}{\kappa} q + i^2 \rho - \frac{h \ \Pi_K N_K l^2}{\left(S - S_K\right) j}\left(T - t\right),$$

$$f_3 = \frac{h \ \Pi_K N_K l}{V c_P S_K}\left(T - t\right) - \mu_{JT} \xi_d \, \frac{\pi V^2 l}{2 \Pi_K \rho_g}.$$

Functions $\psi_i(x)$ (pulses) must satisfy the system of equations [17]:

$$\left.\begin{aligned}
\frac{d\psi_1}{dx} &= \frac{\alpha \ j}{\kappa} R_1 \psi_1 - \left(\frac{\alpha \ j}{\kappa} R_2 - \frac{h \ \Pi_K N_K l^2}{\left(S - S_K\right) j}\right)\psi_2 - \frac{h \ \Pi_K N_K l}{V c_P S_R}\psi_3, \\
\frac{d\psi_2}{dx} &= \frac{j}{\kappa}\psi_1 - \frac{\alpha \ j}{\kappa}\psi_2, \\
\frac{d\psi_3}{dx} &= -\frac{h \ \Pi_K N_K l^2}{\left(S - S_K\right) j}\psi_2 + \frac{h \ \Pi_K N_K l}{V c_P S_K}\psi_3.
\end{aligned}\right\}_{n,p} \tag{11}$$

where $\left.\begin{aligned} R_1 &= 1 + \frac{d \ln \alpha}{dT} T - \frac{d \ln \kappa}{dT}\left(T + \frac{q}{\alpha}\right), \\ R_2 &= R_1 + \frac{1}{Z}\frac{d \ln \sigma}{dT} + \frac{d \ln \kappa}{dT}\left(T + \frac{q}{\alpha}\right). \end{aligned}\right\}_{n,p}$ canonically conjugate to system (5).

With the boundary conditions (transversality conditions):

$$\psi\left(0\right) = \left.\frac{\partial \bar{J}}{\partial y}\right|_{x=0}, \quad \psi\left(1\right) = -\left.\frac{\partial \bar{J}}{\partial y}\right|_{x=1}, \tag{12}$$

where $\bar{J} = J + \sum\left(\nu, g\ \right)$ is expanded functional; ν , g are vectors of undefined constant Lagrangian multipliers and the boundary conditions (7).

Then the boundary conditions for the conjugate system will take on the form:

$$\begin{aligned}
\psi_2^{n,p}\left(0\right) &= \frac{1}{q_n\left(0\right) + q_p\left(0\right)}, \\
\psi_2^{n,p}\left(1\right) &= -\frac{\left(S - S_K\right) j}{l V c_P S_R \left(2t(0) - t_n(1) - t_p(1)\right)}, \\
\psi_3^{n,p}\left(1\right) &= -\frac{1}{2t(0) - t_n(1) - t_p(1)}.
\end{aligned} \tag{13}$$

For the method to be used, the system of equations (5), (7), (11), (13) should be supplemented with functions relating material parameters α, σ, κ to impurity concentration ξ and temperature.

The problem of optimization is to determine such heat carrier flow rate V and such electric current density j

that under restrictions (5), (7), (11), (13) would impart the lowest value to functional J (8). In this case COP (8) will be maximum.

According to the Pontryagin maximum principle, for the minimum of J the following conditions should be met.

1. Current density should satisfy the equality:

$$-\frac{\partial J}{\partial j}+\sum_{n,p}\int_0^1\frac{\partial H\ (\psi,T,q,t,j,V)}{\partial j}dx=0\ . \quad (14)$$

2. The flow rate of heat carrier in the channels should satisfy the equation:

$$-\frac{\partial J}{\partial V}+\sum_{n,p}\int_0^1\frac{\partial H\ (\psi,T,q,t,j,V)}{\partial V}dx=0\ . \quad (15)$$

The system of equations (5), (7), (11), (13) with regard to (14), (15) and numerical solution methods were used to create a program of computer-aided design of optimal parameters of permeable cooling thermoelement.

III. Results of computer-aided design of permeable thermoelement based on Bi$_2$Te$_3$ material

Let us consider the results of computer-aided design of permeable thermoelements with account of the Joule-Thomson effect for the case of air cooling and thermoelectric material legs are made of solid solutions based on Bi_2Te_3 (Fig. 2). These dependences $\alpha_{n,p} = \alpha_{n,p}(T)$; $\sigma_{n,p} = \sigma_{n,p}(T)$; $\kappa_{n,p} = \kappa_{n,p}(T)$ were used in the computation program. The air temperature at inlet to porous thermoelement T_s was assumed equal to the hot junction temperature T_h.

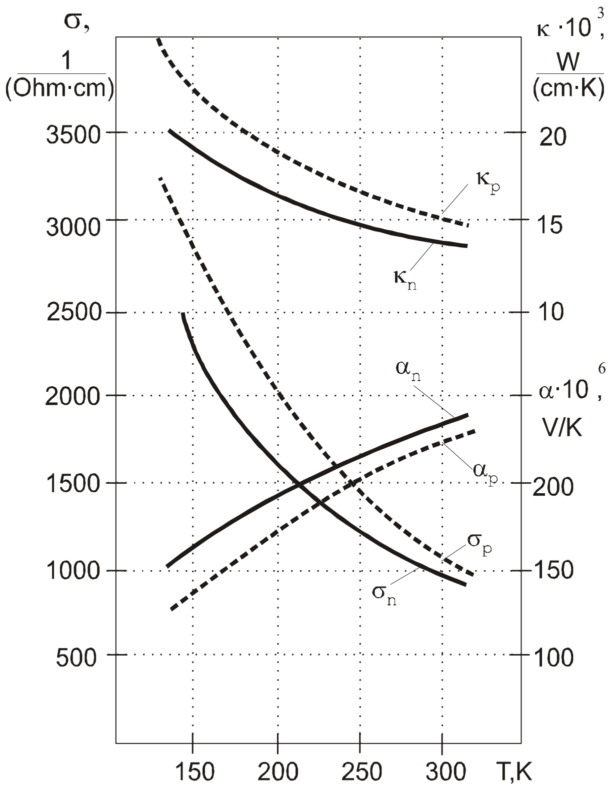

Fig. 2. Temperature dependences of Bi_2Te_3 material parameters.

Characteristics of permeable thermoelement as a function of air velocity in channels V at the ratio S_k/S = 0.5 under optimal density of supply current are shown in Fig. 3. It is seen that COP has maximum according to air pumping velocity which in this case is about 20 cm/s. With increasing air velocity in the channels, COP is

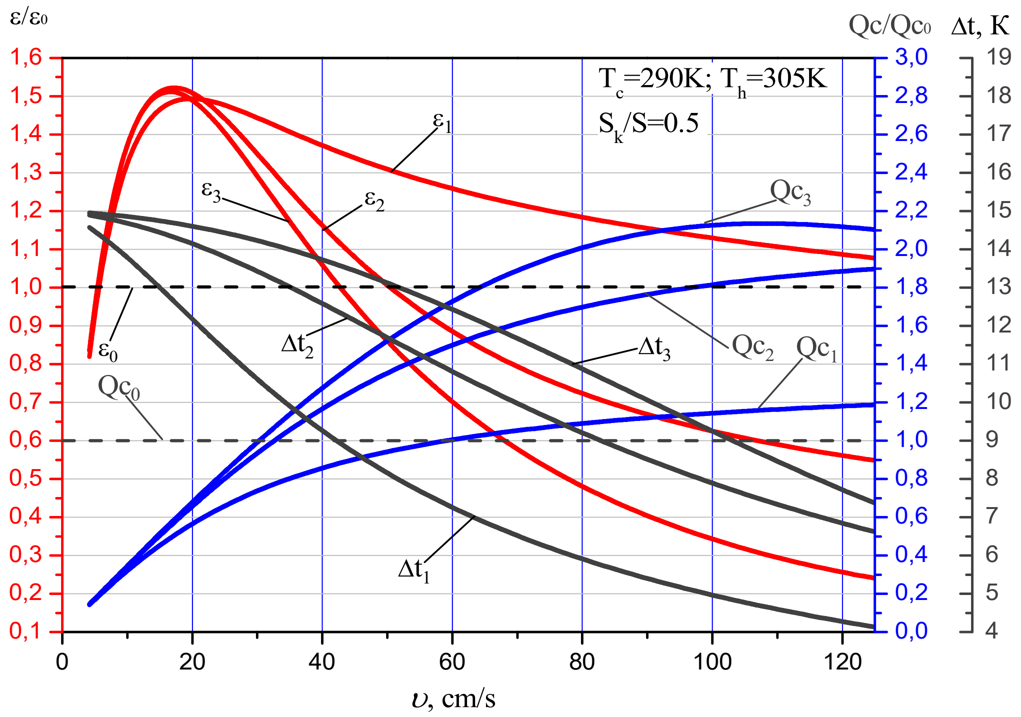

Fig. 3. Dependence of coefficient of performance ε, cooling capacity Q_c with respect to their values for classical thermocouple elements (ε_0, Q_0) and air cooling depth Δt on air velocity in channels (index 1 – effective diameter of channels 0.1cm; 2 – 0.05cm; 3 – 0.033cm).

Table 1

Optimal parameters of permeable thermoelement

ΔT, K	Δt, K	COP_{max}	Q_c, W	Q_h, W	V_{opt}, gr/(cm^2 s)	j_{opt}, A/cm	P, W	U, V	I, A
6.0	5.4	5.65	0.238	0.275	0.0228	5.3	0.042	0.015	2.7
10.0	9.3	3.95	0.312	0.384	0.0219	7.4	0.079	0.021	3.7
14.0	13.1	2.94	0.378	0.498	0.0209	9.5	0.128	0.027	4.8
18.0	17.0	2.28	0.436	0.618	0.0199	11.7	0.191	0.033	5.8
22.0	20.9	1.81	0.486	0.744	0.0188	14.0	0.269	0.038	7.0
26.0	24.8	1.46	0.528	0.878	0.0177	16.3	0.362	0.044	8.2
30.0	28.7	1.18	0.560	1.018	0.0166	18.7	0.471	0.050	9.4
34.0	32.6	0.97	0.583	1.168	0.0155	21.3	0.599	0.056	10.6
38.0	36.6	0.79	0.595	1.327	0.0143	23.9	0.746	0.062	11.9
42.0	40.6	0.65	0.597	1.496	0.0131	26.6	0.915	0.069	13.3
46.0	44.6	0.52	0.586	1.678	0.0118	29.5	1.108	0.075	14.7
50.0	48.7	0.42	0.563	1.874	0.0105	32.5	1.326	0.082	16.2

reduced and at high air velocities it becomes less than in classical thermoelements ε_0. It is not so with cooling capacity, i.e. at low air velocities (up to 30 cm/s) it is less than in classical thermoelements Qc_0, and at high velocities it is greater. Thus, for effective channel diameter 0.05 cm at equal COP values (velocity 50 cm/s) cooling capacity of permeable thermoelements is 40 % larger compared to classical bulk thermoelements. It will enable the air conditioner thermal modes to be provided in a more efficient way.

While analyzing the results, it should be noted that the Joule-Thomson effect has a more pronounced influence on cooling of gases at small channel diameters ($d_k < 0.1$cm). Hence, the smaller channel diameter, the larger the effect. In so doing, it is necessary to provide rather large number of channels in order to guarantee higher cooling power of thermoelement. This situation is realized in the case of using porous materials, suggesting good prospects for using such materials in the permeable cooling thermoelements.

At the same time, reduction of channel diameters increases the pressure difference that has to be created for pumping of air. If this difference is not natural, but created by external means, it leads to increased energy expenditure, hence reduces the thermodynamic efficiency of power conversion.

Optimal parameters of permeable thermoelement based on Bi_2Te_3 material for the mode of maximum coefficient of performance at $T_h = 305$ K depending on temperature difference ΔT. are shown in the Table 1.

It is interesting to study COP increase of permeable thermoelements due to the Joule-Thomson effect. This data is given in Fig. 4 as a growth of COP of permeable thermoelements with the use of the Joule-Thomson effect (dependence 1) and permeable thermoelements without the Joule-Thomson effect (dependence 2) compared to impermeable thermoelements. Dependence 1 is given for the case when the diameter of channels located with density 3800 pcs per 1 cm^2 is 0.01 cm and leg height is 1 cm.

It is evident that the rational use of thermoelectric effects combined with the Joule-Thomson effect allows COP increase as a function of temperature difference by 60 - 70 % as compared to impermeable thermocouple coolers (dependence 1) and by 5 - 8 % (the difference between dependences 1 and 2) as compared to permeable thermoelements wherein the Joule-Thomson effect is minor.

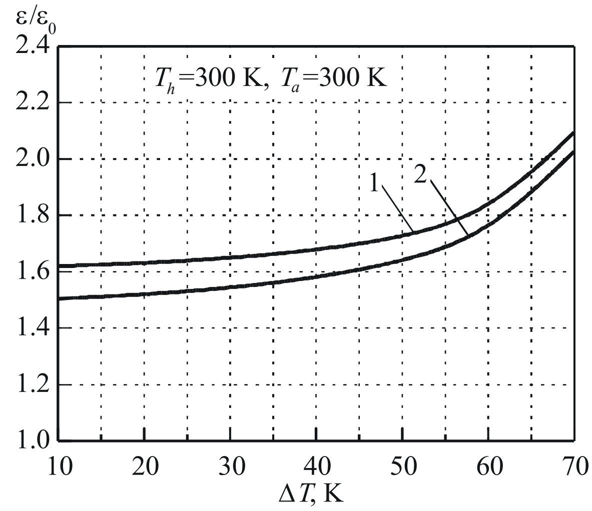

Fig. 4. Coefficient of performance growth compared to traditional impermeable thermoelements as a function of temperature difference. (1 is permeable thermoelement using the Joule-Thomson effect; 2 – permeable thermoelement without the Joule-Thomson effect).

Let's compare the refrigeration coefficient with traditional Peltier thermoelectric modules [19]. For a temperature difference of 33 K, their refrigeration coefficient is 0.6. From table 1 it is seen that the permeable thermocouple when cooling the air to 33 K has a cooling coefficient of 0.9. Thus, the efficiency gain when using permeable thermocouples reaches 50 %. This advantage in terms of refrigeration coefficient indicates the prospects of research aimed at creating permeable thermoelectric air coolers.

Comparison of COP values of such thermoelectric system to other variants discussed in the Introduction, allows a conclusion that thermoelectric air conditioners on the basis of permeable thermoelements hold considerable promise.

Conclusions

Physical model of cooling thermoelement using a combined action of thermoelectric effects and the Joule-Thomson effect for cooling gas flows is represented. Cooling power of thermoelement under maximum COP has maximum according to the diameter of channels, their number and leg height. A deviation from the optimal values of these parameters can result in the essential reduction of useful cooling power.

The results of computer investigations for the case of using Bi_2Te_3 material for thermoelement legs have shown that the rational use of thermoelements allows COP increase by 60 - 70 % as compared to conventional thermocouple elements.

Thermoelectric cooling devices have a number of advantages over other types of refrigeration machines. At present, heat-using or steam refrigerating machines are used in air conditioning systems on ships. In the cold season, the ship's premises are heated by electric, steam or water heaters, ie separate sources of heat and cold are used. With the help of thermoelectric devices in the warm season you can cool the room, and in the cold - to heat. The heating mode is changed to cooling mode by reversing the electric current. In addition, the advantages of thermoelectric devices include: complete absence of noise during operation, reliability, absence of working substance and oil, smaller weight and overall dimensions with the same refrigeration capacity. Comparative data on refrigeration machines for supply chambers on ships show that with the same refrigeration capacity, the mass of the thermoelectric refrigeration machine is by 1.7-1.8 less than the compression. Thermoelectric refrigeration machines for air conditioning systems have a volume of about four and a mass three times less than refrigeration compression machines [20-22].

The disadvantages of thermoelectric cooling devices include insufficient efficiency and high cost. The efficiency of traditional thermoelectric refrigeration machines in comparison with steam is about 20-50% lower [23]. The high cost of thermal cooling devices is associated with high prices for semiconductor materials. However, there are areas where they are already able to compete with other types of refrigeration machines.

This work provides opportunities for a wider use of permeable thermoelectric devices in solving the problems of air thermal stabilization. Such thermoelectric units can be also applied for cooling of chips in modern computers, mobile and telecommunication units, instruments for biological and medical applications

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Оптимізація ефективності проникних термоелектричних елементів для кондиціонування повітря

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Представлена оптималізація проникного термоелемента для термоелектричного кондиціонера на базі. У термоелектричному блоці кондиціонера повітряний потік охолодження за допомогою спільної дії термоелектричних ефектів та ефекту Джоуля-Томсона. Відповідно до методики розрахунку розподілу температури, визначення енергетичних характеристик перетворення енергії та конструкцій термоелементів у режимах максимальної КС. Результати комп'ютерних досліджень для випадків термоелементних ніжок на основі матеріалу Bi2Te3 показали можливість використання коефіцієнта коефіцієнта коефіцієнта корисної дії у 1,6 - 1,7 рази порівняно із звичайними термоелектричними системами.

Ключові слова: термоелектричність, термоелементи, телурид вісмуту, коефіцієнт корисної дії, кондиціонер.

Nomenclature

d – channel diameter (cm)
Π_K - channel perimeter (cm)
T_c - cold temperature of thermoelement (K)
x - coordinate (cm)
S - cross-section area of the thermoelectric legs with the channels (cm^2)
S_K - cross-sectional area of all the channels(cm^2)
i - density of electrical current (A/cm^2)
I - electrical current (A)
P - electrical power (W)
U - electrical voltage (V)
Z - figure of merit of thermoelectric (K^{-1})
p - gas pressure (Pa)
H - Hamiltonian function
c_p - heat carrier heat capacity (Joule/(kg K))
V - heat carrier mass velocity in the channels (kg/(cm^2 s))
T - heat carrier temperature (K)
t - heat carrier temperature (K)
T_a - heat carrier temperature at inlet in thermoelement (K)
υ –heat carrier velocity in the channels (cm/s)
l - height of the thermoelectric legs (cm)
T_h - hot temperature of thermoelement (K)
N_K - number of channels
Q - power of heat flux (W)
j - specific density of electrical current (A/cm)
q - specific heat flux (W/A)
T - temperature of material legs (K)
Pr_c –the Prandtl number for channel wall
Pr_m –the Prandtl number for heat carrier
Re_m –the Reynolds number for heat carrier

Greek symbols
ε - coefficient of performance (efficiency) COP
ψ - components of vector function of pulses
σ - electrical conductivity of material (1/(Ohm·cm))
ρ - electrical resistivity of material (Ohm·cm)
ξ_d - friction coefficient
ρ_g - gas density (kg/cm^3)
h - heat exchange coefficient (W/(cm^2 K))
ξ - impurity concentration (cm^{-3})
μ_{JT} - Joule-Thomson coefficient (K/Pa)
α - Seebeck coefficient of material (V/K)
λ_m – thermal conductivity of gas (W/cm·K)
κ - thermal conductivity of material (W/cm·K)

Subscripts
n - n-type thermoelectric material
p - p-type thermoelectric material
h - hot
c - cold