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THE EFFECT OF HEAT EXCHANGE SYSTEM ON THE EFFICIENCY OF THERMOELECTRIC AIR CONDITIONER

Results of calculation of the efficiency of thermoelectric air conditioner with regard to the effect of heat exchange system are presented. Optimal operating conditions of heat exchange system for achieving the highest air conditioner efficiency are determined.
Key words: air conditioner, heat exchange, thermoelectricity.

Introduction

General characterization of the problem. Efficiency enhancement of thermoelectric air conditioners [1] in the majority of cases comes down to increase in the figure of merit [2] of thermoelectric materials. However, their efficiency to no small degree depends on the heat exchange devices and systems used to transfer thermal energy through thermoelectric power converters (the so-called heat pumps). Preliminary analysis shows that the real efficiency values of thermoelectric air conditioners are much lower than the expected ones even at the achieved values of material figure of merit. It is due to the fact that in the design and optimization of thermoelectric equipment use is mostly made of simplified physical models [3-6] that do not take into account the quality of heat exchange systems, the thermal and electric losses that may deteriorate considerably the energy characteristics of thermoelectric air conditioner. In Ref. [7], a procedure for calculation of thermoelectric air conditioner efficiency for generalized physical models of thermoelectric power converters is discussed.

The purpose of this work is to analyze the effect of real heat exchange system on the efficiency of thermoelectric air conditioner and to optimize its operation. For this purpose, multi-parameter computer optimization of thermoelectric air conditioner efficiency was carried out with regard to the experimentally determined characteristics of heat exchange system.

1. Physical model of thermoelectric air conditioner

A physical model of thermoelectric air conditioner is shown in Fig. 1. Closed space 1 is cooled by thermoelectric cooling modules 7. Heat abstraction system is composed of the cold and hot loops 5, 10. The cold loop comprises a liquid-air heat exchanger 3 with a fan 2, a liquid pump 4 and a liquid heat exchanger 6. The cold loop assures heat abstraction from cooling chamber 1 to thermoelectric modules. The hot loop comprises a liquid heat exchanger 8, a liquid pump 9 and a liquid-air heat exchanger 11 with a fan 12. The hot loop assures heat abstraction from thermoelectric modules to the environment. The electric energy consumers in the physical model are thermoelectric modules of electric power W_m, fans of liquid-air heat exchangers of electric power W_{v1} and W_{v2}, and liquid pumps of electric power W_{n1} and W_{n2} for the cold and hot loops, respectively.

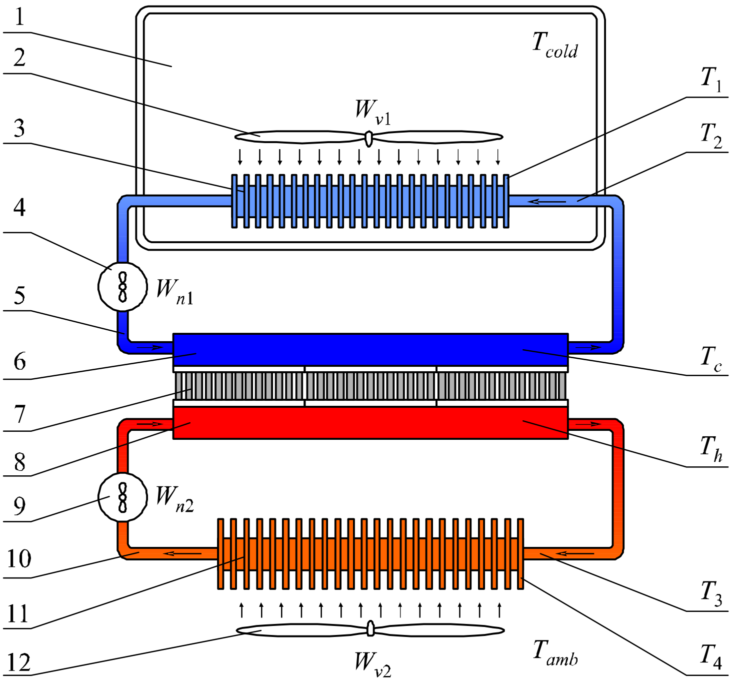

Fig. 1. Physical model of thermoelectric heat pump: 1 – cooling chamber; 2, 12 – fans; 3, 11 – liquid-air heat exchangers; 4, 9 – liquid pumps, 5, 10 – liquid loops; 6, 8 – liquid heat exchangers, 7 – thermoelectric cooling modules.

2. Thermoelectric air conditioner efficiency

The air conditioning system is characterized by such parameters as cooling capacity Q_0, that is, the amount of heat abstracted from cooling chamber (it is a function of temperature difference on thermoelectric modules, heat leak-in through air-conditioner chamber insulation from the ambient and the quality of heat exchange system), as well as coefficient of performance ε which is a ratio between cooling capacity Q_0 and electric energy spent on supply of thermoelectric modules, fans and liquid pumps. It is obvious that the real-life coefficient of performance of thermoelectric air conditioner will be much different from the coefficient of performance of thermoelectric modules. In so doing, it will depend on the electric power values of all system consumers:

$$\varepsilon(W_{n1}, W_{n2}, W_{v1}, W_{v2}, W_m, N) = \frac{Q_0}{W_{n1} + W_{n2} + W_{v1} + W_{v2} + W_m} \quad (1)$$

where N is the number of thermoelectric modules.

Thus, to achieve maximum coefficient of performance of thermoelectric air conditioner, one should find the optimal operating conditions for each of heat exchange system components. For this purpose, in the present paper we employ the experimental dependences of parameters of heat exchange system components on their electric power consumption and seek the multi-parameter maximum of coefficient of performance using numerical methods.

2.1. Thermal and energy balance equations

The air conditioner thermal balance equations may be written as:

$$\begin{cases} Q_{r1} = Q_{\text{TEB}} \\ Q_{r2} = Q_{\text{TEB}} + W_0 \end{cases} \quad (2)$$

where Q_{r1} is heat which is absorbed on liquid-air heat exchanger of the cold loop. It defines air-conditioner cooling capacity Q_0 and corresponds to heat which is absorbed on the cold side of thermopile, Q_{r2} is heat which is dissipated on liquid-air heat exchanger of the hot loop. It corresponds to heat which is released on the hot side of thermopile, Q_{TEB} is thermopile cooling capacity, W_0 is thermopile supply power.

The balance of temperatures is given by:

$$T_{amb} = T_{cold} - \Delta T_{r1} - \Delta T_{t1} + \Delta T_{\text{TEB}} - \Delta T_{t2} - \Delta T_{r2} \quad (3)$$

where T_{amb} is ambient temperature, T_{cold} is designed temperature in the isolated chamber, $\Delta T_{r1} = T_{cold} - T_1$ is temperature drop on the liquid-air heat exchanger of the cold loop, $\Delta T_{t1} = T_2 - T_c$ is temperature drop on the liquid heat exchanger of the cold loop, $\Delta T_{\text{TEB}} = T_h - T_c$ is temperature drop on the thermopile, $\Delta T_{t2} = T_h - T_3$ is temperature drop on the liquid heat exchanger of the hot loop, $\Delta T_{r2} = T_3 - T_{amb}$ is temperature drop on the liquid-air heat exchanger of the hot loop.

Let us introduce the following functional dependences of air conditioner component characteristics.

$Q_m(W_m, \Delta T, T_h)$ is cooling capacity of thermoelectric modules as a function of the electric power of modules, temperature drop on the modules and the hot side temperature of modules;

$G(W_n, N)$ liquid flow rate in the heat-exchange loop as a function of pump supply power and the number of thermoelectric modules;

$Q_r(W_n, W_v, \Delta T_r, N) = F_r(W_n, W_v, N)\cdot\Delta T_r$ is thermal power which is transferred by liquid-air heat exchanger as a function of liquid pump and fan supply powers and the difference in temperature between the air and liquid at the heat exchanger inlet;

$Q_t(\Delta T_t, W_n, N) = F_t(W_n, N)\cdot\Delta T_t$ is thermal power which is transferred by liquid heat exchanger as a function of temperature difference between thermoelectric module surface and liquid at the heat exchanger inlet, liquid pump and fan supply powers and temperature difference between the air and liquid at the heat exchanger inlet.

Based on this, the following relations will be obtained to find temperature drops listed in (3):

$$Q_{r1} = F_r(W_{n1}, W_{v1}, N)\cdot\Delta T_{r1} = Q_0 \quad (4)$$

$$Q_{r2} = F_r(W_{n2}, W_{v2}, N)\cdot\Delta T_{r2} = Q_0 + W_0 \quad (5)$$

$$Q_{t1} = F_t(W_{n1}, N)\cdot\Delta T_{t1} = Q_0 \quad (6)$$

$$Q_{t2} = F_t(W_{n2}, N)\cdot\Delta T_{t2} = Q_0 + W_0 \quad (7)$$

The air conditioner cooling capacity will be found from equation (8)

$$Q_0 = Q_{\text{TEB}}(W_0, \Delta T_{\text{TEB}}, T_h) \quad (8)$$

The expression for temperature drop on thermopile ΔT_{TEB} will be obtained by substituting (4) – (7) into (2):

$$\Delta T_{\text{TEB}} = T_{amb} - T_{cold} + Q_0\left(\frac{1}{F_r(W_{n_1}, W_{v1}, N)} + \frac{1}{F_t(W_{n1}, N)}\right) + \\ + \left(Q_0 + W_0\right)\left(\frac{1}{F_r(W_{n_2}, W_{v2}, N)} + \frac{1}{F_t(W_{n2}, N)}\right). \quad (9)$$

The expression for T_h will be obtained from the equation

$$T_h = T_{amb} + \Delta T_{r2} + \Delta T_{t2}. \quad (10)$$

Substituting (4) and (6) into (10), we obtain:

$$T_h = T_{amb} + \left(Q_0 + W_0\right)\left(\frac{1}{F_r(W_{n_2}, W_{v2}, N)} + \frac{1}{F_t(W_{n2}, N)}\right). \quad (11)$$

The expressions (8), (9) and (11) form a system of equations to find the air conditioner cooling capacity Q_0 which is solved with respect to Q_0, ΔT_{TEB}, T_h for given T_{amb}, T_{cold} values and $F_r(W_n, W_v, N)$, $F_t(W_n, N)$ and $Q_{\text{TEB}}(W_0, \Delta T_{\text{TEB}}, T_h)$ functions.

The air conditioner coefficient of performance is found from (1). The objective function of optimization will be air conditioner coefficient of performance, and optimization parameters – the electric powers of air conditioner components.

2.2. Optimization methods

The above described awkward and complicated optimum criteria motivate the use of numerical methods of seeking the optimal value of objective function.

The objective function of thermoelectric air conditioner – coefficient of performance – is a nonlinear function that depends on the combination of parameters which, in turn, are expressed implicitly, using a plurality of empirical equalities. So, it is impossible to use the methods of search for the first and second-order extremes (due to the impossibility of finding the derivatives). A search for the optimal coefficient of performance value employed gradient-free zero-order method – a modified Hook-Jeeves method [8].

At each iteration step of the main program cycle, a system of nonlinear equations (8 – 11) is solved and cooling capacity is found. Coefficients of approximating polynomials that are used to determine the empirical relations between the physical parameters of optimization program are calculated.

3. Thermoelectric air conditioner optimization

3.1. Empirical functions of parameters of thermoelectric air conditioner components

Thermoelectric modules. Based on the experimental investigations of the dependence of cooling capacity of thermoelectric cooling module Altec-127 on the supply power and the hot and cold heat exchanger temperatures, in the numerical calculations the function of module heat capacity Q_m was approximated by the analytical dependences:

$$Q_m(W_m, \Delta T, T_h) = \left[F_m(W_m)\left(1 - 0.0015\Delta T\right) - \left(1.334 - 0.00233T_h\right)\Delta T\right] \times \\ \times \left(0.07217 + 0.00317T_h\right), \quad (12)$$

where

$$F_m = \left(8.45\sqrt{W_m - 0.115} - 0.37W_m + 3.25\right). \quad (13)$$

Liquid pumps. Dependence of liquid flow rate in heat exchange loop on the pump power and the number of modules was found as follows:

$$G(W_n, N) = \frac{\Delta P_{\max}(W_n)}{r_g + NR_g^t}, \qquad (14)$$

where $\Delta P_{\max}(W_n)$ is dependence of maximum pump pressure on its power, R_g^t is hydraulic resistance of liquid heat exchanger, r_g is hydraulic resistance of heat exchange loop without heat exchangers.

From the experiments with the liquid pump the following dependences were established:

$$\Delta P_{\max}(W_n) = 0.01283 W_n \quad \text{(atm)}, \qquad (15)$$

$$G(W_n, N) = \frac{0.01283 W_n}{6.31 \cdot 10^{-4} + N \cdot 1.835 \cdot 10^{-3}} \quad \text{(ml/s)}. \qquad (16)$$

Liquid-air heat exchangers. Experimental studies were used to establish the values of power that can be transferred from liquid to air depending on the difference in temperature between water at heat exchanger inlet and air, liquid losses in heat exchange loop and fan supply power $Q_r(\Delta T_r, G, W_v)$. Taking into account that $G = G(W_n, N)$, and $Q_r \sim \Delta T_r$, the value Q_r was obtained as follows:

$$Q_r(W_n, W_v, \Delta T, N) = F_r(W_n, W_v, N) \cdot \Delta T_r, \qquad (17)$$

where $F_r(W_n, W_v, N)$ is experimental function which characterizes the heat exchanger.

For the heat exchanger under study function F_r was approximated as follows:

$$F(W_n, W_v, N) = \left[15.5783 + 0.3402 G(W_n, N) - 0.0018 G(W_n, N)^2\right] \times \\ \times \left[0.15 + 0.14125 W_v - 0.00437 W_v^2\right]. \qquad (18)$$

Liquid heat exchangers. Dependence of liquid heat exchanger power $Q_t(\Delta T_t, G)$ on the difference in temperature between water at heat exchanger inlet and heat exchanger surface, and on water flow rate in the heat exchange loop was experimentally determined. Taking into account that $G = G(W_n, N)$ and $Q_t \sim \Delta T_t$ dependence Q_t will be sought as follows:

$$Q_t(\Delta T_t, W_n, N) = F_t(W_n, N) \cdot \Delta T_t, \qquad (19)$$

where $F_t(W_n, N)$ is experimental function characterizing the heat exchanger. For the heat exchanger under study function F_t was approximated as:

$$F_t(W_n, N) = N\left[2.5349 + 0.08292 G(W_n, N) - 3.02648 \cdot 10^{-4} G(W_n, N)^2\right]. \qquad (20)$$

3.2. Results of thermoelectric air conditioner optimization

As a result of thermoelectric air conditioner optimization, the operating conditions of air conditioner components were found whereby its coefficient of performance has a maximum.

Using the algorithms and program described in paragraph 2, the coefficient of performance of air conditioner ε_0 was calculated for the following input parameters of the problem:

ambient temperature T_{amb} = 20, 25, 30, 35, 40 °C,

reduction of temperature in the chamber $\Delta T = T_{amb} - T_{cold}$ = 10, 15, 20 °C.

In Tables 1 – 3 are listed the results of calculation of maximum coefficient of performance $\varepsilon_{\max}$ of air conditioner and its cooling capacity depending on the number of thermoelectric modules N.

Besides, in the Tables are listed the supply power values of air conditioner systems whereby coefficient of performance has a maximum.

Table 1

Maximum coefficient of performance of air conditioner at T_{amb} = 20 °C, ΔT = 10 °C

N	ε_{max}	Q_0, W	W_0, W	W_{n1}, W	W_{v1}, W	W_{n2}, W	W_{v2}, W
2	0.519	24.38	21	5	8	5	8
4	0.628	32.01	25	5	8	5	8
6	0.667	36.01	28	5	8	5	8
8	0.676	38.58	31	5	8	5	8.1
10	0.668	41.86	35	5	8.5	5	9.5
20	0.587	41.36	48	5	10	5	12

Table 2

Maximum coefficient of performance of air conditioner at T_{amb} = 20 °C, ΔT = 15 °C

N	ε_{max}	Q_0, W	W_0, W	W_{n1}, W	W_{v1}, W	W_{n2}, W	W_{v2}, W
2	0.422	22.34	27	5	8	5	8
4	0.475	29.92	35	5	8	5	8
6	0.481	32.68	42	5	8	5	8
8	0.468	36.94	50	5	8	7	11
10	0.448	40.06	58	5	9.5	9	12
20	0.331	40.99	87	5	11	21	12

Table 3

Maximum coefficient of performance of air conditioner at T_{amb} = 20 °C, ΔT = 20 °C

N	ε_{max}	Q_0, W	W_0, W	W_{n1}, W	W_{v1}, W	W_{n2}, W	W_{v2}, W
2	0.334	20.03	34	5	8	5	8
4	0.353	28.70	51	5	8	8	9.5
6	0.340	38.48	75	5	8	16	10
8	0.320	43.0	87	5	9	22	12
10	0.26	40.2	124	5.6	10.5	25	12
20	0.18	39.3	162	6	12	28	12

Fig. 2 gives a comparison of the coefficient of performance of thermoelectric modules and air conditioner under other optimal operating conditions of thermoelectric air conditioner components.

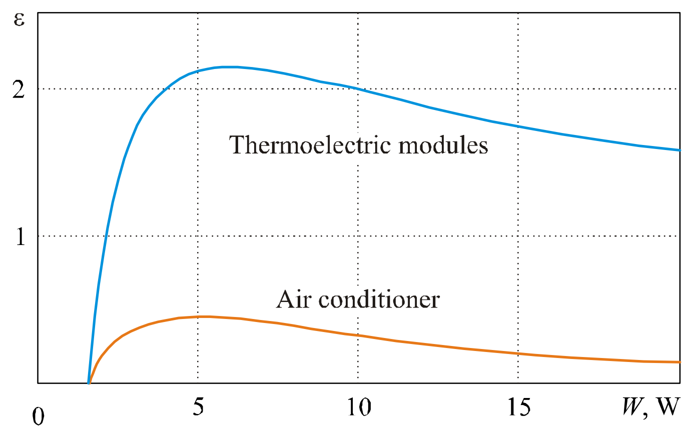

Fig. 2. Dependences of coefficient of performance of thermoelectric modules and thermoelectric air conditioner on the supply power of thermoelectric modules T_{amb} = 20 °C, ΔT = 15 °C.

Conclusions

1. The physical and mathematical models, the algorithms and computer program of search for multi-parameter maximum of coefficient of performance of thermoelectric air conditioner have been developed.
2. For the specific designs of thermoelectric air conditioner, multi-parameter maxima of coefficient of performance have been found in the operating power ranges of thermopile, liquid pumps and air fans for specified cooling depth.
3. It has been established that even under the optimal operating conditions of air conditioner components the coefficient of performance of thermoelectric air conditioner differs by a factor of ~ 7 from that of thermoelectric modules. This testifies to the necessity of improving the components of heat exchange systems of thermoelectric air conditioner.

References

1. L.I. Anatychuk, *Thermoelectricity. Volume1. Thermoelectric Power Converters* (Kyiv, Chernivtsi: Institute of Thermoelectricity, 2003), 376 p.
2. L.I. Anatychuk, Current Status and Some Prospects of Thermoelectricity, *J.Thermoelectricity* 2, 7-20 (2007).
3. L.I. Anatychuk, K. Misawa, N. Suzuki, Ya. Takai, Yu.Yu. Rozver, Thermoelectric Air Conditioner for Rooms, *J.Thermoelectricity* 1, 53-56 (2003).
4. Yu.Yu. Rozver, Thermoelectric Air Conditioner for Vehicles, *J.Thermoelectricity* 2, 70-72 (2003).
5. http://www.fujitaka.com
6. http://www.hi-z.com
7. L.I. Anatychuk, A.V. Prybyla, The Effect of Heat-Exchange Systems on the Efficiency of Thermoelectric Devices, *J.Thermoelectricity*, 3, 39-43 (2012)
8. V.M. Verzhbitsky, *Numerical Methods (Linear Algebra and Nonlinear Equations): Manual for Higher Education Institutions* (Moscow: "ONIX 21 Century" Publishing House, 2005), 432 p.

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