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Thermoelectric Coolers with Friction Steam Brakes

D.A. Volchenko[1], M.V. Kindrachuk[2], N.A. Volchenko[1], M.V. Savchin[3], Y.M. Savchin[3], T.V. Bolony[3]

[1] *Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine*
[2] *National Aviation University, Ukraine*
[3] *Drohobych Specialized College of Oil and Gas, Ukraine*

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In the materials of the article, the following issues are considered in relation to this problem: the efficiency of temperature reduction in a thermoelectric cooler; the nature of the destruction of an electric charge by thermal impulses; operating modes of thermopiles in brake friction pairs. The purpose of the article is to reduce the value of the ratio between the Peltier ("useful") and Joule ("harmful") effects in electric and thermal currents circulating in the thermopile branches, and the use of thermoelectric cooling in the friction pairs of the tape-shoe brake of the drawworks. The thermopiles installed in the friction linings of the brake band on its incoming and outgoing branches operated in the modes of a thermoelectric cooler and a thermoelectric generator, respectively. It has been established that when the energy loading is quasi-leveling in terms of the belt sweep angle of the pulley, the following is achieved on average: a decrease in energy loading to 20 %, an increase in the dynamic coefficient of friction by 11 %, and a decrease in liner wear by 8.5 % when they operate in the range of surface-bulk temperatures below the acceptable value for their materials.

Keywords: Thermoelement, Peltier effect, Thermopile, Friction pair, Brake.

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1. INTRODUCTION

The idea of using a variable composition of thermoelectrics to increase the conversion efficiency of a thermoelectric device operating in a wide temperature range was originally proposed by AF Ioffe.

Studies of thermoelectric batteries show that to eliminate the quantitative difference between thermal and electric currents in the Peltier and Joule effects, it is necessary to "slow down" charge carriers in an n-type semiconductor, which will make it possible to eliminate the imbalance between electric and thermal currents in the circuit branches.

There are at least two possibilities for increasing the efficiency: using a variable concentration of charge carriers: optimization of the efficiency parameter Z at each point of the branch in the working temperature range and the use of the distributed Peltier effect [1]. The application of the distributed Peltier effect is considered one of the promising ways to increase the efficiency of thermoelectrics. In this case, it is tempting to completely compensate for the Joule heat using the distributed Peltier effect [2]. As shown in [3], in the optimized leg with full Joule heat compensation, the electrical conductivity at the cold end of the leg is two orders of magnitude higher than that at the hot end, and the modulus of the differential thermoelectric power is 4 times less. In [3], to maintain the optimal value of Z in PbTe, carriers of only one sign are also used - electrons, the concentration of which is determined by the concentration of the dopant. It is recommended to maintain the efficiency parameter close to the maximum at each point of the leg by changing the composition of the material along the length of the thermoelement leg.

Real low-temperature thermoelectrics with high efficiency do not have a wide band gap, therefore, it is necessary to take into account the intrinsic charge carriers [4-7].

This article discusses the following issues in relation to this problem: the efficiency of temperature reduction in a thermoelectric cooler; the nature of the destruction of an electric charge by thermal impulses; operating modes of thermopiles in brake friction pairs.

The aim of the work is to reduce the value of the ratio between the Peltier and Joule effects for electric and thermal currents in thermopiles and the use of thermoelectric cooling in friction pairs of a band-shoe brake of a drawworks.

2. THE EFFICIENCY OF TEMPERATURE REDUCTION IN A THERMOELECTRIC COOLER

The efficiency of thermoelectric coolers depends on many factors. Therefore, we will consider the main ones.

In Fig. 1 schematically shows a battery of semiconductor thermoelements connected in series.

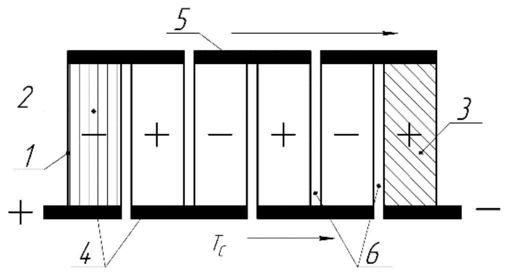

Fig. 1 – Battery of thermoelements connected in series: 1 – cylindrical shell; 2, 3 – cylindrical rods made of electronic (–) and hole (+) semiconductors, constituting the legs of the thermoelement; 4, 5 – connecting metal plates forming thermoelement joints; 6 – insulating air gap

When passing current through thermoelements, along with the "useful effect" – the absorption of Peltie heat proportional to the current strength, – there is a "harmful effect" – the release of Joule heat in the thermoelement branchesproportional to the square of the current strength. The calculation shows that, in a first approximation, half of the Joule heat comes to cold junctions and decreases the cooling obtained due to the Peltier effect. At zero current, both effects disappear and no cooling will occur; on the other hand, with a sufficiently large current, the Joule heat will exceed the Peltier heat and the cooling will turn into heating; therefore, there is an optimum current at which the cooling effect is maximized (Fig. 2). In order to find this current, we write an expression for the algebraic sum (Q_J): the Peltie heat absorbed at the junction, the Joule heat supplied to it:

$$Q_J = -\Pi_{1,2}J + \frac{1}{2}J^2R, \tag{1}$$

where $\Pi_{1,\,2}$ – Peltie coefficient; R – thermoelement resistance;

$$R = l\left(\frac{\rho_1}{s_1} + \frac{\rho_2}{s_2}\right), \tag{2}$$

where l, s_1, s_2 and ρ_1, ρ_2 – the length, cross-section and resistivity of its branches, respectively.

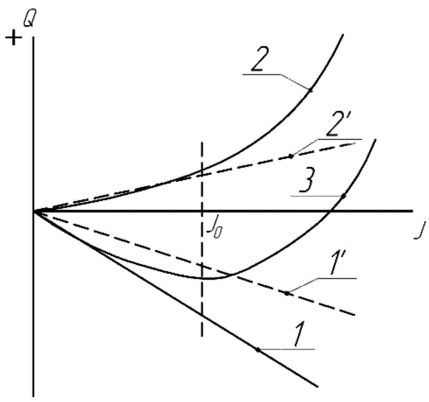

Fig. 2 – Dependence of the amount of heat supplied to the cold junctions on the current (J): 1 – Peltie heat absorbed at the junction in the classical scheme; 2 – Joule heat supplied to the junction; 3 – algebraic sum of Joule and Peltier heats (Q_J): J_0 – optimal current: *1′*, *2′* – in the improved circuit

Differentiating, we find that Q_J reaches a maximum at a current

$$J_0 = \frac{\Pi_{1,2}}{R}, \tag{3}$$

$$\left(Q_J\right)_{\max} = -\frac{\Pi_{1,\,2}^2}{2R}. \tag{4}$$

where K – thermal conductivity coefficient of thermoelement.

From (4) it follows that the lower the thermal conductivity coefficient of the thermo-element, the greater the amount of heat (Q_J) max that can be absorbed in its cold junction, i. e., the greater its cooling capacity. In this case, a pair of thermoelements operates in the thermoelectric cooler mode. This completes the analysis of the classic thermoelectric battery circuit.

Of course, the better the thermal insulation of the cooling junctions, the lower the temperature they will reach. Let us first consider the simplest case when the heat flux from the environment can be neglected. Under these conditions, the temperature of the cold junction will decrease until the heat flux carried by the thermal conductivity of the thermoelement legs (appearing due to the temperature difference between the cold and hot junctions) balances the heat Q_J absorbed at the junction: the stationarity condition, therefore, will have the form [9]:

$$K_1 = \frac{1}{l\delta}\left(\chi_1 s_1 + \chi_2 s_2\right), \tag{6}$$

where δ, K_1 – thickness of the surface layer of the thermoelement and its thermal conductivity coefficient; χ_1 and χ_2 – specific thermal conductivity of the legs; according to (4):

$$\left(T_0 - T\right)_{\max} = \frac{\left(Q_J\right)_{\max}}{K_1} = \frac{\Pi_{1,\,2}^2}{2K_1R}. \tag{7}$$

If we are talking about a thermopile, then its refrigerating capacity is determined by the ratio of its area to thickness and does not depend on the number of thermoelements from which it is assembled. Indeed, if we reduce, for example, 2 times the cross section of the branches, then the optimal current and cooling capacity of each element decreases 2 times, but the number of thermoelements doubles, and thus the total cooling capacity of the battery will remain the same.

However, in friction pairs of brakes during electrothermal friction, impulsive interaction of their microprotrusions occurs.

3. DISCUSSION OF THE RESULTS

Instead of a heat impulse, a normal force impulse is used to create a local expansion of the film, which can be calculated by calculation into a specific load impulse. The latter method can be used both in charge and current measurements, it does not require a difficult handling procedure to find the distribution of charges, since during the propagation of a jump in specific loads through a metal microprotrusion (contact spot), the local compression is the same at all points. On the other hand, the technique requires complex measuring equipment for its implementation [2].

Installed the dependence of the areas (A_c) of the contact spots of metal microprotrusions and the number (n) on the acting impulse normal forces (N). These dependences were obtained analytically. In this case, the following data were used: characteristics of the microgeometry of the surfaces of microprotrusions above the middle line of the profile R_p and the maximum radius of curvature of the protrusions r_{max}; a is the distance between microprotrusions; physical and mechanical characteristics of the material – elastic modulus E (Young's modulus), Poisson's ratio μ, specific electrical resistance of the material p', impulse normal force N, compressing the contact [8, 9].

Analysis of the received data showed the following:

– an increase in the distance between microprotrusions and the area of their contact spots with a simultaneous increase in their impulse normal forces contributed to a decrease in the specific loads in the contact spot zones;

– the number of contact spots contributed to an increase in their areas, and, as a consequence, to a decrease in specific loads.

Experimental data concerning the dependence of the electrode potential (φ_y) on the sliding speed (V_{sl}) and the pulsed specific load (p), varying by large (p_l) and small (p_s) jumps on the contact spots of the microprotrusions of metalpolymer friction pairs showed the following:

– an increase in the sliding speed is accompanied by an increase in impulse specific loads, and as a consequence, a decrease in the electrode potential;

– jumps in pulsed specific loads on the contact spots of microprotrusions contribute to an increase in the electrode potential by the end of the end of the process of frictional interaction.

To ensure the thermal uniformity of loading of both individual zones of friction linings with incoming and outgoing surfaces, and each incoming and outgoing surface of the lining in a brake device, let us consider the operation of thermopiles in the mode of a thermoelectric generator and a thermoelectric cooler using the example of a tape-block brake of a drawworks winch.

In Fig. 3 shows a fragment of a band-shoe brake with thermoelectric cooling (a), its cross section (b), friction unit (c) and semiconductor rods with n- and p-type conductivity (d) (Russian patent № 2134368). Graphene (–) zinc antimony ZnSb (+) nanotubes were used as semiconductor materials [1].

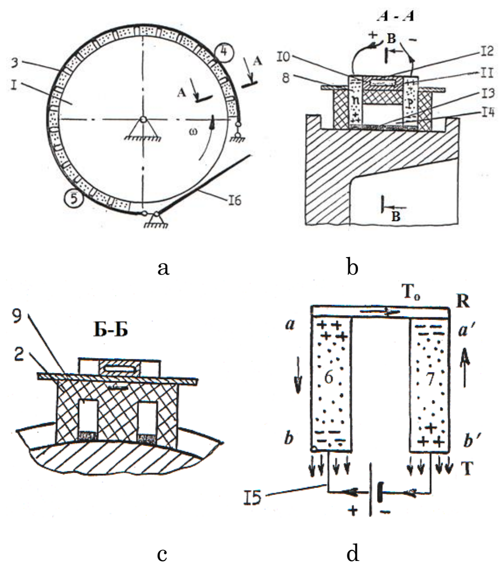

Fig. 3 – Band-shoe brake with thermoelectric cooling: 1 – brake pulley; 2 – friction linings; 3, 4 and 5 – brake band with running and running branches; 6, 7 – thermoelements with n- and p-type conductivity; 8, 9 – holes and protrusions in the brake band; 10, 11 and 12 – heat pipe with zones of evaporation and condensation; 13, 14 – connecting metal bridge and the gap between it and the permissible wear of the friction lining; 15 – external electrical circuit; 16 – control lever

The intensification of this type of cooling is achieved by increasing the current supplied to the branches of the thermoelectric refrigerator. Thus, the more loaded the brake, the greater the temperature difference appears at the junctions of thermoelectric generators of the runaway branch *5* of the tape *3*, the higher the current it generates, which, summed up with the power supply current, contributes to a deeper cooling of the friction surfaces of the linings *2* of the running branches *4* tape *3*.

Heat removal from the cold junctions of the thermoelectric generator and the hot junctions of the thermoelectric refrigerator is carried out using the heat pipe *10*. Heat is transferred from the thermoelements *6* and *7* to the evaporation zone *11*, i. e. directly to the heat carrier, which, when heated, turns into steam and moves to the condensation zone *12*, and then returns again to the evaporation zone *11*. Subsequently, the cycles in the heat pipe *10* are repeated.

Intensive cooling of the friction pairs of the band-shoe brake allows to increase its operating parameters, reduce thermal stresses in the brake pulley, and also increase the resource of the friction pairs. This principle of operation of thermopiles can be used in other types of braking devices.

Theoretical and experimental studies of thermoelectric coolers in friction pairs of a band-shoe brake of a drawworks made it possible to state the following:

– if we are talking about a thermopile, then its refrigerating capacity is determined by the ratio of its area to thickness and does not depend on the number of thermoelements from which it is assembled. Indeed, if we reduce, for example, 2 times the cross-section of the branches, then the optimal current and cooling capacity of each element decreases 2 times, but the number of thermoelements increases 2 times, and, thus, the total cooling capacity of the battery will remain the same;

– to eliminate the difference between electric and thermal currents in the Peltier and Joule effects, it is necessary to "slow down" charge carriers in a semiconductor with n-type conductivity, which will make it possible to eliminate the imbalance between them;

– in addition to the length of the thermopile chain, in the calculation formula for determining its thermal conductivity, it is necessary to take into account the thickness of the surface layer of the pulley rim, as well as its thermal resistance;

– the possibility of operation of thermopiles installed in the friction linings of the brake band on its incoming and outgoing branches, in the modes, respectively, of a thermoelectric refrigerator and a thermoelectric generator;

– with quasi-leveling of the energy load by the belt angle of the pulley, the following is achieved on average: a decrease in the energy load up to 20 %, an increase in the dynamic coefficient of friction by 11 % and a decrease in the wear of the linings by 8.5 % when they work in the range of surface-bulk temperatures below the permissible for their materials.

Thus, the application of a thermoelectric cooler in the friction pairs of a tape-shoe brake of a drawworks is shown and its efficiency is estimated.

REFERENCES

1. A.A. Petrik, N.A. Volchenko, P.Yu. Purgal, D.A. Volchenko, *Friction Units. Monograph* (KSTU, Krasnodar: 2003).
2. O.I. Markov, *Phys. Semicond.* 56 No 1, 48 (2021).
3. I.A. Drabkin, L.B. Ershova, *Phys. Technol. Semicond.* **56** No 1, 3 (2021).
4. A. Barinov, L. Casalis, L. Grigoraffi, M. Kiskinova, *Phys. Rev.* **63** No 8, 3081 (2001).
5. S. Bhunia, D.N. Bose, *J. Appl. Phys.* **87** No 6, 2931 (2000).
6. V.L. Kuznetsov, *Functionally Graded Materials for Thermoelectric Applications* In *CRC Thermoelectrics Handbook: Macro to Nano* (Ed. by D.M. Rowe) (CRC Press: Taylor & Francis Group, Boea Raton: London-N.Y: 2006).
7. D.A. Volchenko, M.V. Kindrachuk, N.A. Volchenko, N.B. Klochko, A.O. Yurchuk, *J. Nano- Electron. Phys.* **12** No 6, 06020 (2020).
8. M.V. Kindrachuk, O.I. Volchenko, D.O. Volchenko, V.S. Skrypnyk, A.V. Voznyi, *Mater. Sci.* **54** No 6, 843 (2019).
9. N. Volchenko, A. Volchenko, D. Volchenko, P. Poliakov, V. Malyk, D. Zhuravlev, V. Vytvytskyi, P. Krasin, *East.-Eur. J. Enterprise Technol.* 1/5 (97), 47 (2019).

Термоелектричні охолоджувачі з фрикційними паровими гальмами

Д.А. Волченко[1], М.В. Кіндрачук[2], Н.А. Волченко[1], М.В. Савчін[3], Ю.М. Савчін[3], Т.В. Болоний[3]

[1] *Івано-Франківський національний технічний університет нафти і газу, Україна*
[2] *Національний авіаційний університет, Київ, Україна*
[3] *Дрогобицький фаховий коледж нафти і газу, Україна*

У статті розглянуті питання ефективності зниження температури в термоелектричному охолоджувачі; природи руйнування електричного заряду тепловими імпульсами; режимів роботи термобатарей у парах тертя гальма. Мета роботи полягала у зменшенні величини співвідношення між ефектами Пельтьє («корисним») і Джоуля («шкідливим») електрични-ми та тепловими струмами, що циркулюють у гілках термобатарей, та застосування тер-моелектричного охолодження в парах тертя стрічково-колодкового гальма бурової лебідки. Термобатареї, встановлені у фрикційні накладки гальмівної стрічки на її гілки, працювали в режимах, відповідно, термоелектрохолодильника і термоелектрогенератора. Установлено, що при квазівирівнюванні енергонавантаженості по куту охоплення стрічкою шківа досягається в середньому: зниження енергонавантаженості до 20%, підвищення динамічного коефіцієнта тертя на 11% і зменшення зносу накладок на 8,5% при їх роботі в інтервалі поверхневих об'ємів. матеріалів.

Ключові слова: Термоелемент, Ефект Пельтьє, Термопара, Пара тертя, Гальмо.