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IMPROVEMENT OF THE EFFICIENCY OF A SOLAR THERMOELECTRIC BATTERY

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A refined model for calculation of the heat transfer inside a thermoelectric temperature transducer of the module type is considered as applied to the structure of a solar thermoelectric battery. An investigation is made of the dependence of the useful electric power of the battery on the geometric characteristics of its thermomodules and the structural parameters of the battery. It is shown that for each value of the external load optimum values of the cross-sectional area and height of the thermoelement arms exist, at which the maximum useful electric power is realized.

Introduction. One of the alternative ways of obtaining electric energy is introduction of systems allowing direct conversion of the thermal energy of the sun into electricity by means of thermoelectric temperature transducers that are based on use of the Seebeck and Peltier effects.

At present, thermoelectric transducers of the module type, i.e., thermomodules structurally made of two thin ceramic plates between which series-connected thermoelements of the p- and n-type are placed, are widely used. Modern technologies make it possible to manufacture modules with dimensions 30×30 mm and smaller in which up to 70–80 thermoelement pairs with a cross-sectional area of their arms of up to 0.5×0.5 and a height of 0.5 to 5 mm are arranged. Depending on the materials used and the methods of supply and removal of heat, a temperature difference of 200 to 700^{o}C can be attained on such thermomodules. Here, the electric power taken from a module can reach 3 to 15 W.

The limited use of thermoelectric transducers as electric-power sources has been attributed, on the one hand, to the low efficiency of materials (no more than 5%) and, on the other hand, to the absence of inexpensive and heat-resistant materials for the thermoelements. However, recent break-throughs in the field of materials science for thermoelements [1, 2] and the compactness and small dimensions of the modules allow us to turn our attention once again to the development of thermomodule-based solar thermoelectric batteries, relying on up-to-date materials with an increased Q-factor in combination with optimization of their geometric characteristics and use of efficient heat supply and removal systems.

The structure of a solar thermoelectric generator suggested in the present work can compete successfully with a photoelectric battery in both reliability and cost. For comparison, the cost of a photoelectric battery varies, as judged from different estimates, from \$5 to \$250 per watt of generated electric power, and the predicted cost of a thermoelectric battery can range from \$1 to \$3 per watt of produced electric power. The service life of present-day photoelectric batteries does not exceed 5 years, while that of thermoelectric ones attains 15 years [2]. Moreover, a thermoelectric battery has one more merit: by regulating the flow rate of the heat-transfer agent in the cooling circuit of the cold face, one can obtain a heat-transfer agent with the required temperature for domestic or production needs. In this case, the utilization factor of solar energy increases substantially.

Formulation of the Problem and Derivation of the Equations. In deriving the equations, we made some assumptions not influencing the main results:

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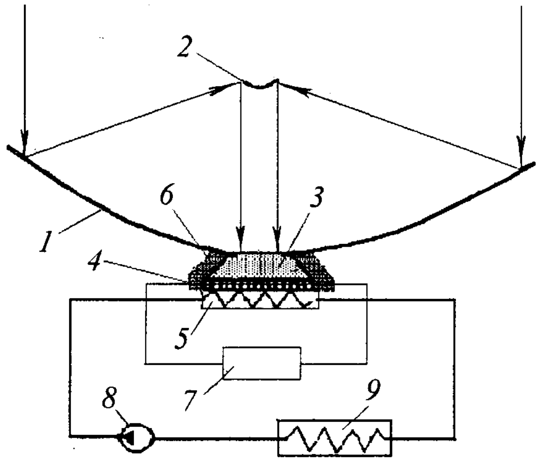

Fig. 1. Schematic of a solar thermoelectric battery: 1) parabolic focusing reflector; 2) parabolic guiding reflector; 3) conical radiation detector; 4) battery of thermomodules; 5) cooling jacket; 6) heat insulation; 7) electric-power consumer; 8) pump; 9) coolant of a heat-transfer agent.

a) the thermoelectrical properties of the materials do not depend on the temperature difference (according to modern approaches, they are prescribed with respect to the volume-mean temperature of the thermoelements);

b) the thermoelectric resistances of the commutation elements are low compared to the resistances of the thermoelements, and they can be neglected;

c) the Joule and Thomson thermal effects are not taken into account because of their smallness;

d) the cross-sectional areas of the thermoelement arms are the same and are constant over height.

Electrical part. It is known that when a temperature difference $\Delta t_m = (t_{hot} - t_{cold})$ is created on the thermojunctions an thermoelectromotive force develops at the thermomodule ends [3]:

$$E = 2ne\,(t_{hot} - t_{cold})\,,$$

and upon connecting an external load the current in the circuit and the useful electric power of the module are determined by the relations [3, 4]

$$I = \frac{2ne\Delta t_m}{R + r_m}\,, \quad W = \frac{(2ne)^2\,(\Delta t_m)^2\,R}{(R + r_m)^2}\,,$$

where $r_m = 2n(\rho l/f)$ is the internal electrical resistance of the module.

To obtain the required values of the power and the volt-ampere characteristics of the thermoelectric battery, the modules inside the battery are arranged in series-parallel groups. Then, according to Kirchhoff's law, we have

$$I_b = \frac{NM\,2ne\,\Delta t_m}{MR + Nr_m}\,, \tag{1}$$

$$W_b = \frac{N^2M^2\,(2ne\,\Delta t_m)^2\,R}{(MR + Nr_m)^2}\,. \tag{2}$$

Thermal part. The solar thermoelectric battery is shown schematically in Fig. 1. The concentrator of solar radiation consists of two confocal specular parabolic reflectors, namely, the major focusing and the minor guiding ones. The top of the major reflector has a hole (whose diameter coincides with the upper base of the radiation detector) through which a concentrated flux falls on a radiation detector made of a highly heat-conducting material in the form of a truncated cone. The surface of the upper base is blackened. The thermomodules are fastened to the lower base by the "hot" faces, and the jacket of the cooling system is attached to their "cold" faces. The side surface of the radiation detector is heat-insulated.

Taking into account the special structure of the thermomodules, we consider the heat transfer inside the module in more detail. We represent the module in the form of two plates connected to each other by $2n$ columns of thermoelements. Heat exchange between the plates is attributable to the following mechanisms of heat transfer: heat conduction of the thermoelements arms $2n(\lambda_m f/l)$, equivalent heat conduction of air in the free volume between the module faces $\lambda^*_{air}(F_m - 2nf)/l$, and radiant heat transfer between the module faces $\alpha_r(F_m - 2nf)$. Here $\lambda^*_{air} = \varepsilon_{con}\lambda_{air}$, $\varepsilon_{con} = c(\mathrm{Gr\ Pr})^m$ is the convection coefficient [5]; the numerical values of c and m are a function of the argument (Gr Pr):

$$\mathrm{Gr\ Pr} = 10^3 - 10^6\,, \quad c = 0.105\,, \quad m = 0.3\,,$$

$$\mathrm{Gr\ Pr} = 10^6 - 10^{10}\,, \quad c = 0.4\,, \quad m = 0.2\,,$$

$\alpha_r = \varepsilon_{red}\sigma T^3_{hot}(1 + \theta + \theta^2 + \theta^3)$ is the coefficient of radiant heat transfer, $\varepsilon_{red} = 1/(\varepsilon_{hot} + 1/\varepsilon_{cold} - 1)$ is the reduced emissivity [5], and $\theta = T_{cold}/T_{hot}$ is the reduced temperature.

To derive the dependence of the useful electric power of the battery on the thermoelectric and geometric characteristics of the thermoelements, we consider the system of balance equations

$$Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T^4_w = k_{red}(t_w - t_{hot})\,, \tag{3}$$

$$Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T^4_w = (t_w - t_{cool.h.t.a})/(1/k_{red} + 1/kF + 1/\alpha F_{cold}) + Q_P + W\,, \tag{4}$$

$$kF\,(t_{hot} - t_{cold}) = \alpha F_{cold}\,(t_{cold} - t_{cool.h.t.a})\,. \tag{5}$$

Here $k_{red} = \lambda_{det}F_m(b + 1)MN/2bh$ is the reduced heat-transfer coefficient of the radiation detector, $kF = MN[2nf\lambda_m/l + \lambda^*_{air}(F_m - 2nf)/l + \alpha_r(F_m - 2nf)]$ is the total coefficient of heat transfer between the hot and cold faces of the modules, and Q_{sol} is the total solar-radiation flux concentrated on the area of the upper base of the radiation detector:

$$Q_{sol} = r'_{foc.ref}\,r'_{g.ref}\,A_{sol}\,F_{foc.ref}\,q_{sol}\,, \tag{6}$$

Q_P is the Peltier heat. For a thermomodule, the Peltier heat can be expressed by the relation $(Q_P)_m = (2ne)^2 T_{hot}\Delta t_m/R + r_m$, while for a battery composed of series-parallel groups of modules the expression for the Peltier heat acquires the form

$$Q_P = \frac{N^2M\,(2ne)^2\,T_{hot}\Delta t_m}{MR + Nr_m}\,, \tag{7}$$

$t_{cool.h.t.a} = (t^{in}_{cool.h.t.a} + t^{out}_{cool.h.t.a})/2$ is the mean temperature of the heat-transfer agent in the cooling zone of the cold faces of a module.

From (3) and (5) it follows that

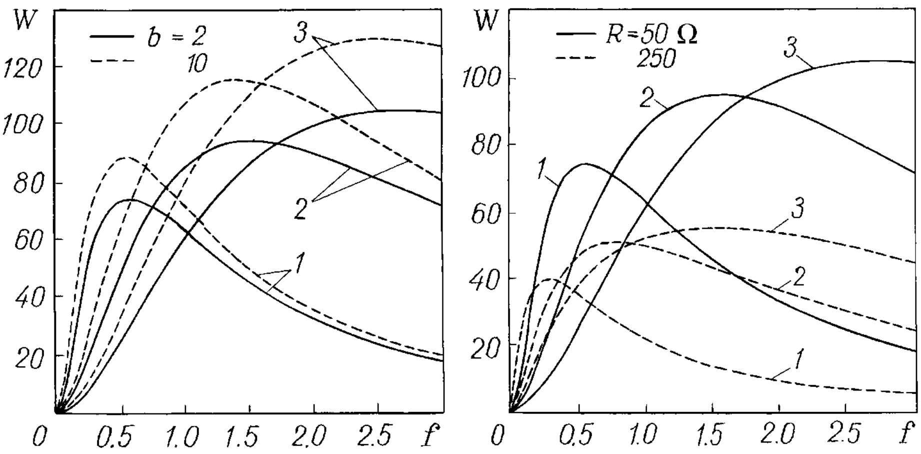

Fig. 2. Useful electric power of the battery versus geometric characteristics of the thermoelements, degree of conicity of the radiation detector, and resistance of the external load: 1) l = 1.5 mm; 2) 4.0; 3) 7.0. W, W; f, mm^2.

$$\Delta t_m = (kF^*/kF)\,[t_w - t_{cool.h.t.a} - (Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4)/k_{red}]\,, \tag{8}$$

where $kF^* = 1/(1/kF + 1/\alpha F_{cold})$ is the equivalent heat-transfer coefficient.

Substituting (8) into (2) and (7) and introducing the notation

$$a = (NM\,2ne)/(MR + Nr_m)\,,\quad \Delta t^* = [t_w - t_{cool.h.t.a} - (Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4)/k_{red}]\,, \tag{9}$$

we obtain expressions for W_b and Q_P:

$$W_b = Ra^2\,(kF^*/kF)^2\,(\Delta t^*)^2\,, \tag{10}$$

$$Q_P = aN{\cdot}2ne\,\Delta t^*\,[T_w - (Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4)/k_{red}]\,. \tag{11}$$

Substituting (10) and (11) into (4), we arrive at the following expression for determination of T_w:

$$Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4 = (t_w - t_{cool.h.t.a})/(1/k_{red} + 1/kF + 1/\alpha F_{cold}) + Ra^2\,(kF^*/kF)^2 \times$$

$$\times [t_w - t_{cool.h.t.a} - (Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4)/k_{red}]^2 + aN{\cdot}2ne\,[t_w - t_{cool.h.t.a} - (Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4)/k_{red}] \times$$

$$\times [T_w - (Q_{sol} - F_w\,\varepsilon_w\,\sigma\,T_w^4)/k_{red}]\,,$$

which represents a transcendental equation, which can be solved, for instance, by the method of successive approximations with the use of computers.

Having determined T_w, we can determine all necessary characteristics of the battery. To implement this algorithm, we have developed a package of programs on a personal computer.

Analysis of the Results. To illustrate the procedure, we carried out parametric calculations of a battery of 10 modules (N = 5, M = 2) containing 128 thermoelement pairs each. The thermoelectric characteristics of the arms are taken to be as follows: λ_m = 2 W/(m·K), $e = 2\cdot10^{-4}$ V/K, and $\rho = 2\cdot10^{-5}$ Ω·m; the dimensions of the module faces are 40 × 40 mm. It is assumed that temperature control of the cold face is accomplished by a cooling loop with the parameters: αF_{cold} = 5 W/K, $t_{cool.h.t.a}$ = 50°C. The resistance of the external load is

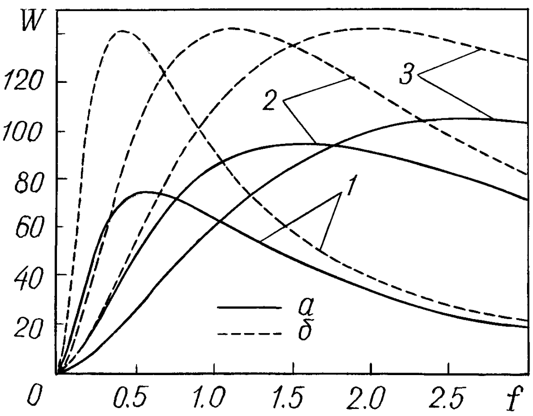

Fig. 3. Useful electric power of the battery versus geometric characteristics of the thermoelements with (a) and without (b) allowance for radiative-convective heat transfer: 1) l = 1.5 mm; 2) 4.0; 3) 7.0.

taken to be R_1 = 50 Ω and R_2 = 250 Ω. The characteristics of the radiation detector are as follows: height h = 0.04 m, thermal conductivity λ_{rec} = 100 W/(m·K), and degree of conicity b_1 = 2 and b_2 = 10.

The optical and geometric characteristics of the solar-radiation concentrator are chosen so as to provide a value of the heat flux incident on the radiation detector equal to 1500 W.

Figure 2 shows the dependence of the useful electric power W on the geometric characteristics of the thermoelements for different values of the degree of conicity of the radiation detector and the resistance of the external load. As follows from the plots, in addition to the structural and load parameters, the battery power depends substantially on the height l and cross-sectional area f of the arms; here the function $W(f)$ has a maximum whose value depends on l.

The plots in Fig. 3 illustrate the influence of the additional mechanisms of heat transfer (radiation, convection) in the thermomodules on the energy characteristics of the battery. From the data presented it follows that the indicated heat-transfer mechanisms substantially influence W in the region of small cross-sectional areas of the thermoelement arms, which is precisely characteristic of thermomodules. This conclusion is inconsistent with results obtained by available procedures [4], according to which the power of a heat generator depends, in addition to the heat and load parameters, only on the thermoelectrical properties of the materials (for evaluation of the efficiency, use is made of the Q-factor $Z = e^2/\lambda\rho$). In this connection, existing calculation methods give a large error in calculating thermal-battery characteristics.

Thus, optimizing the structural elements of the battery and the geometric characteristics of the thermomodules, one can improve the efficiency (W/Q_{sol}) of a battery to 10–15%.

The coefficient of solar-energy conversion can be increased further by using a heat-transfer agent for domestic or production purposes. Regulating its flow rate, one can obtain a heat-transfer agent of the required temperature at the cooling-jacket outlet. Thus, for the example under consideration, by using water with a flow rate of 0.6 liter/min as the heat-transfer agent, one can obtain water with a temperature of 65°C at the cooling-jacket outlet.

Conclusion. The procedure presented makes it possible to choose optimum geometric characteristics of thermomodules that in combination with a conical form of the radiation detector improve the efficiency of the thermoelectric battery and decrease the cost of a unit of the electric energy generated.

NOTATION

p-type, thermoelectric material with hole conductivity; n-type, thermoelectric material with electronic conductivity; T, absolute temperature, K; t, temperature, °C; λ, thermal conductivity, W/(m·deg); ρ, specific electrical resistivity, $\Omega\cdot$m; *e*, thermoelectromotive force of the thermoelement, V/K; σ, Stefan–Boltzmann constant, W/($m^2\cdot K^4$); *R*, resistance of the external load, Ω; *r*, internal electrical resistance, Ω; *I*, current strength, A; *W*, useful electric power, W; α, heat-transfer coefficient, W/($m^2\cdot$K); *F*, area of the module base, the radiation detector, and the heat-transfer surface, m^2; *f*, cross-sectional area of the thermoelement arm, m^2; *l*, height of the thermoelement arm, m; *h*, height of the radiation detector, m; Gr, Grashof number; Pr, Prandtl number; *c*, coefficient; *n*, number of thermoelements (pairs of arms) in the module; *N*, number of series-connected modules in the circuit; *M*, number of parallel circuits in the battery; *m*, exponent; ε_{con}, coefficient of convection; ε, emissivity; A_{sol}, coefficient of absorption of solar radiation; r', coefficient of reflection; *Q*, total heat flux, W; *k*, overall heat-transfer coefficient, W/($m^2\cdot$K); *q*, surface density of the heat flux, W/m^2; $b = F_{low.surf}/F_{upp.surf}$, degree of conicity of the radiation detector. Subscripts: m, module; b, battery; con, convective; r, radiant; air, air; det, detector (of radiation); red, reduced; cold, cold; h, hot; upp.surf, upper base of the radiation detector; w, wall; low.surf, lower base of the radiation detector; cool.h.t.a, cooling heat-transfer agent; foc.ref, focusing reflector; g.ref, guiding reflector; sol, solar. Superscripts: *, symbol of equivalency; in, inlet; out, outlet.

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