

Thermoelectric cooler for small gas flows

© O.N. Uryupin

Ioffe Institute, St. Petersburg, Russia

E-mail: o.uryupin@mail.ioffe.ru

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A sectioned thermoelectric cooler capable of reducing gas temperature to ~ 240 K was designed. Based on the calculation results, a prototype thermoelectric cooler was manufactured and tested, effectively solving the problem.

Keywords: thermoelectric, sectioned cooler, cooling capacity, gas flow.

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At present, a pressing task in the field of direct energy conversion is to expand the scope of application for thermoelectric converters [1]. One of the application areas of thermoelectric coolers is controlling the gas flow temperatures and air conditioning [2,3]. At the same time, such systems may be of interest for cooling small gas flows or thermostating small objects without rigid attachment of thermoelectric modules to them. The use of the conventional thermoelectric module in such devices is inefficient, since the module's cooling capacity is low in the case of high temperature differences providing significant gas cooling [4,5]. This paper proposes to use for these purposes a sectioned cooler consisting of several modules with separated heat flows. Gas sequentially contacts cold junctions of these modules and, thus, gets cooled gradually. The first modules operate at low temperature differences and, therefore, exhibit high cooling capacity.

The below-described calculation of the chain of thermoelectric modules was performed within a simple model that neglects the temperature dependence of kinetic coefficients. Each of those modules is designed independently of the others, however, the heat flow to its cold junctions depends on the gas temperature change by the previous module.

Such modules are calculated based on the equation describing energy balance at the thermoelement cold junctions [4,5]:

$$\frac{1}{2} \left(\frac{\rho_n}{S_n} + \frac{\rho_p}{S_p} \right) LI^2 + \frac{1}{L} (\kappa_n S_n + \kappa_p S_p) (T_h - T_c) + \frac{Q_0}{N} - (\alpha_p - \alpha_n) T_c I = 0, \quad (1)$$

where ρ , α , κ are the specific electrical resistance, coefficients of thermoelectric power and thermal conductivities of the thermoelectric material, respectively, S and L are the thermocouple branch area and height (indices n and p mark the parameters related to the n and p thermocouple branches), I is the electric current, N is the number of thermocouples in the module, T_c and T_h are the temperatures of cold and hot junctions, respectively. Thermoelement cooling

capacity $Q_0 = C_0(T_0 - T_c)$ is equal to the heat quantity released per second at the cold junctions during the gas flow cooling, C_0 is the gas flow heat capacity, T_0 is its initial temperature. The outlet gas temperature is assumed to be equal to the temperature of the thermoelement cold junctions.

Introducing variables v and μ defined by ratios

$$v^2 = \frac{I^2 L^2}{S_n S_p} \frac{S_n \rho_p + S_p \rho_n}{\kappa_n S_n + \kappa_p S_p}, \quad (2)$$

$$\mu^2 = (\kappa_n S_n + \kappa_p S_p) \left(\frac{\rho_n}{S_n} + \frac{\rho_p}{S_p} \right), \quad (3)$$

reduce equation (1) to

$$\sqrt{z} v T_c - \frac{1}{2} v^2 - (T_h - T_c) - C(T_0 - T_c) \frac{v}{\mu} = 0, \quad (4)$$

where $z = \left(\frac{\alpha_p - \alpha_n}{\mu} \right)^2$, $C = \frac{C_0}{IN}$.

From equation (4), it easy to find the cold junction temperature:

$$T_c = \frac{v^2/2 + T_h + C v T_0/\mu}{1 + \sqrt{z} v + C v/\mu}. \quad (5)$$

When current I and thermoelement height L are specified, and kinetic coefficients of the thermoelectric materials are known, the cold junction temperature depends on the cross-sectional area of any branch, e.g. S_p , and ratio between the branch cross-sections S_p/S_n . It is well known [4] that optimal ratio S_p/S_n is defined as

$$\frac{S_p}{S_n} = \sqrt{\frac{\kappa_n \rho_p}{\kappa_p \rho_n}}. \quad (6)$$

Substituting this ratio into (2) and (3), obtain

$$\mu = \sqrt{\kappa_n \rho_n} + \sqrt{\kappa_p \rho_p}, \quad (7a)$$

$$v = \frac{IL}{S_p} \sqrt{\frac{\rho_p}{\kappa_p}}. \quad (7b)$$

The optimal p -branch cross-sectional area S_p is found by minimizing expression (5) with respect to parameter ν which, as per definition (7b), is inversely proportional to S_p . Optimal value of ν is related to other module parameters by formula

$$\nu = \frac{-1 + \sqrt{1 - 2(\tilde{C} + \sqrt{z})(\tilde{C}T_0 - (\tilde{C} + \sqrt{z})T_h)}}{\tilde{C} + \sqrt{z}}, \quad (8)$$

where $\tilde{C} = C/\mu$. Substitution of this expression into (7b) allows determining the optimal p -branch cross-section S_p .

The same calculation procedure may be applied to the next module of the cooler under consideration, but, for heat load Q_0 , initial gas temperature T_0 should be replaced by temperature T_c of the previous module. Kinetic coefficients of p - and n -type bismuth and antimony chalcogenides may be considered equal with sufficient accuracy, since they are close in magnitude and their temperature dependences are neglected in calculation.

The numerical algorithm for optimizing the cooler was as follows. Measured temperature dependences $\alpha(T)$, $\rho(T)$ and $\kappa(T)$ were approximated by polynomials. Certain initial temperature differences on the modules were preset, and their average values were used to determine kinetic coefficients. Then, optimal ratios S_p/L and cold junction temperatures of all the cooler modules were calculated at a given current. Based on the calculated junction temperatures, new values of the kinetic coefficients were determined. This iterative procedure converged quite rapidly. The calculation showed that the result scarcely depends on the ratio of thermoelement branch areas; therefore, p and n branches of the designed cooler had identical cross-sections.

Prior to calculating thermoelectric coolers on the samples of p and n materials, specific resistance (Fig. 1, *a*) was measured using alternating current which allows elimination of the sample non-isothermality caused by the Peltier effect, thermal conductivity (Fig. 1, *c*) was measured using the absolute stationary method in high vacuum ($p < 10^{-4}$ mm Hg), and, in addition, thermoelectric power coefficient (Fig. 1, *b*) was measured. The measurement error was 4% for specific resistance, 5% for the thermoelectric coefficient, and 8% for the thermal conductivity coefficient.

Using the above-described method, a chain of thermoelectric modules constituting the cooler was calculated; each module consisted of a single thermocouple. The calculations did not take into account contact resistances, heat transfer losses, heat influxes, and nature of the gas flow heat exchange in the coil soldered to the thermoelement cold junctions. Therefore, the actual gas cooling will be somewhat less than calculated. Calculations for the optimal gas flow cooler with the heat capacity of 0.085 W/K (4 l/min) are given in the Table.

The calculations show that, starting from the 23rd thermoelement, increment ΔT becomes less than 0.5 K. Therefore, it is reasonable to limit the number of module

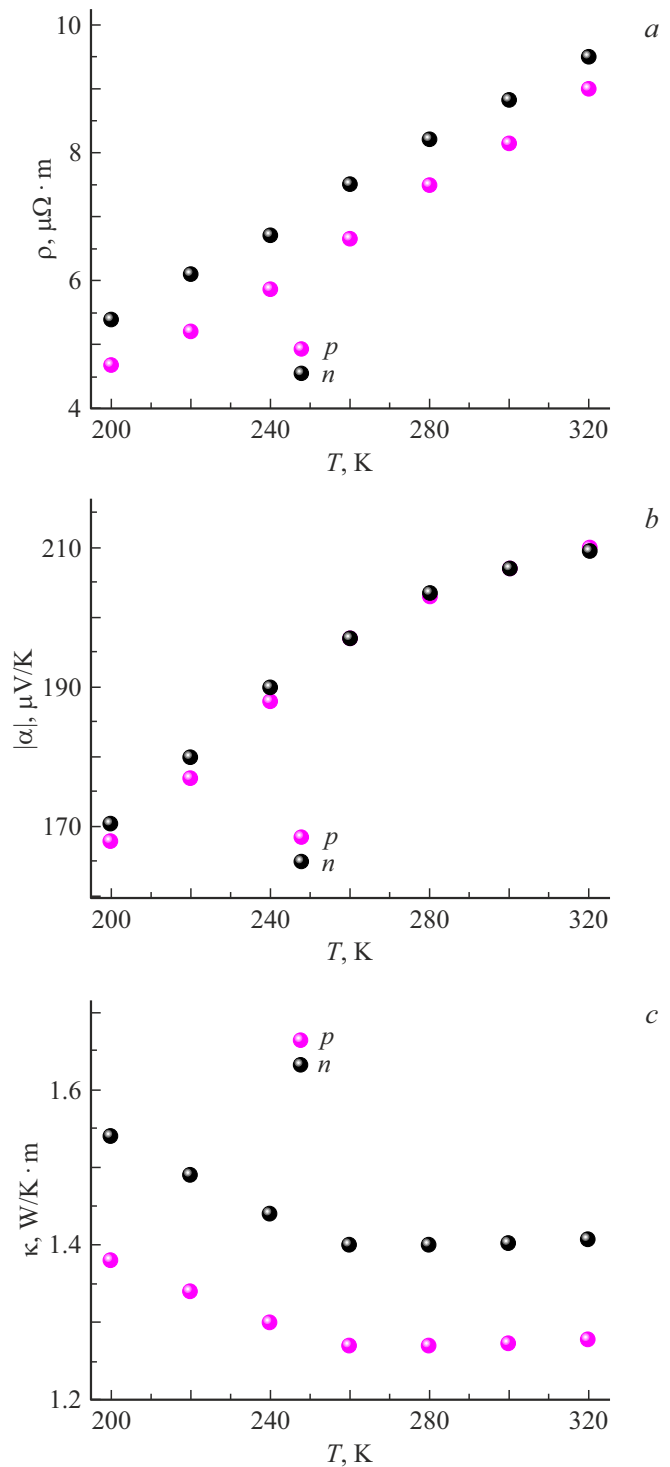


Figure 1. Temperature dependences of specific resistance (*a*), thermoelectric power (*b*) and thermal conductivity (*c*) of the p - and n -type thermoelectric materials. The color figure is presented in the electronic version of the article.

thermocouples to twenty-three. The cross-sectional area of the initial thermoelement branches decreases significantly with increasing the number of a thermoelement. The terminal thermoelements operate in the mode close to

Parameters of the thermoelectric cooler at initial gas temperature $T_0 = 300$ K, hot junction temperature $T_h = 305$ K, heat capacity of the cooled gas flow 0.085 W/K, thermoelement branch height $L = 1.8$ mm, and operating current $I = 10$ A

Thermoelement No.	ΔT , K	S , mm ²	P , W
1	10.1	9.61	1.37
2	18.4	7.61	2.73
3	25.4	6.60	4.08
4	31.3	5.97	5.42
5	36.4	5.54	6.76
6	40.8	5.23	8.09
7	44.6	4.99	9.41
8	47.9	4.80	10.73
9	50.7	4.65	12.04
10	53.3	4.53	13.35
11	55.5	4.43	14.66
12	57.4	4.34	15.97
13	59.1	4.27	17.27
14	60.7	4.21	18.57
15	62.0	4.15	19.87
16	63.2	4.11	21.16
17	64.2	4.07	22.46
18	65.1	4.04	23.75
19	65.9	4.01	25.05
20	66.7	3.98	26.34
21	67.3	3.96	27.63
22	67.9	3.94	28.92
23	68.4	3.92	30.21
24	68.8	3.91	31.50
25	69.2	3.89	32.79

Footnote. ΔT is the thermoelement temperature difference, S is the thermoelement cross-sectional area, P is the total power released at hot junctions.

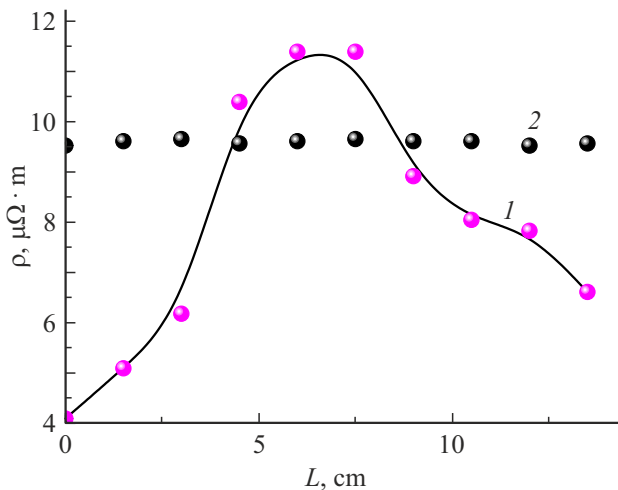


Figure 2. Distribution of specific electrical resistance along the crystalline (1) and extruded (2) samples.

$\Delta T_{\max}$ and bring T_c closer to the minimum possible one; their cross-sections remain almost unchanged.

The described cooler assembled from thermoelements with different branch cross-sections provides the highest gas



Figure 3. Outside view of the cooler with tinned cooling surface.

flow cooling but is difficult to manufacture. Therefore, we used in the sectioned cooler thermoelements with branch cross-sections approximately equal to that of the last two-thirds of thermocouples.

The thermoelement branches are made from bismuth and antimony chalcogenides. Single crystals of these thermoelectric materials exhibit higher thermoelectric efficiency than pressed materials [6]. However, there was revealed a strong heterogeneity of thermoelectric properties of the available samples (Fig. 2). Therefore, the cooler was fabricated using an extruded material with more homogeneous properties.

The created thermoelectric cooler is a non-separable unit consisting of 23 thermoelements. Each branch is 1.8 mm in height and 4 mm² in cross-section. The heat transfer working (liable to cooling) surface is divided into seven sections (Fig. 3). To the thermoelements, a common tubular coil is soldered with 90-degree solder; the flowing gas is first

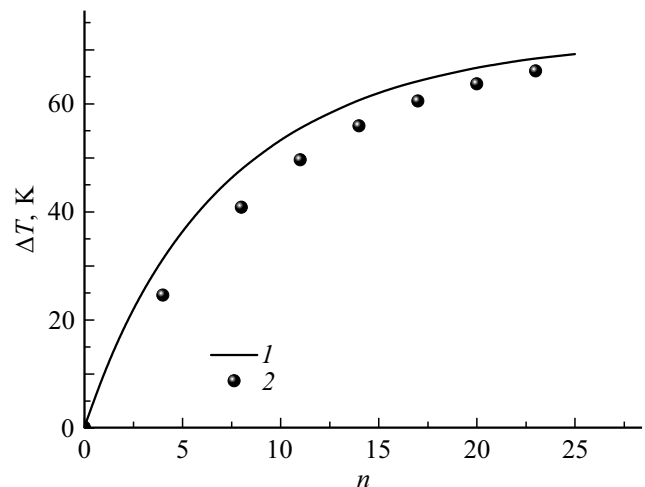


Figure 4. Distribution of temperature differences at thermocouples constituting the cooler (n is the thermoelement No in the cooler). 1 — calculated dependence for the optimal module, 2 — experimental dependence for the created module.

cooled by sections containing four thermoelements. The cooler is powered by direct current of 10 A.

Results of testing the cooler are presented in Fig. 4 that shows temperature differences at the sections' cold junctions measured by the TMK microthermocouples accurately to better than 2.5 %. The same figure presents for comparison the relevant theoretical curve. The observed deviations of experimental results from calculations are quite expected. They are explained by the approximate character of calculations which neglect the temperature dependences of kinetic coefficients, contact resistances, heat transfer losses and heat influxes.

Thus, this paper shows that the use of sectioned thermoelectric coolers for cooling small gas flows provides an increase in the cooling efficiency.

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Conflict of interests

The author declares that he has no conflict of interests.

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