The Multistage Thermoelectric Devices with Inhomogeneous Legs

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Abstract

The contributions of distributed Seebeck effect (DSE) and distributed Peltier effect (DPE) into enhancing the performance of one and multistage thermoelectric devices (TED) (generators (TEG), coolers (TEC), and heaters (TEH)) with inhomogeneous legs are examined once more by theoretical and experimental technique to reveal physical mechanism and perspective of applications of effects in power industry.

Introduction

The thermoelectrics show the "bulk" effects in common with the "contact" ones, both being of the same physical nature. The "bulk" effects are due to Seebeck coefficient drops distributed along the length of the sample ($\Delta\alpha = \alpha_{p(n)} - \alpha_{p'(n')}$), the "contact" ones– due to the drops at the joints of thermocouple ($\alpha = \alpha_p - \alpha_n$) [1]. DSE was discovered by A.Volta in 1794, one of the DPE variety – Thomson effect (TE), by W.Thomson in 1851 [2]. As a rule $\Delta\alpha/\alpha < 0{,}1$, so just the "contact" effects were used the first in fundamental research and applications (Fig.1) [3].

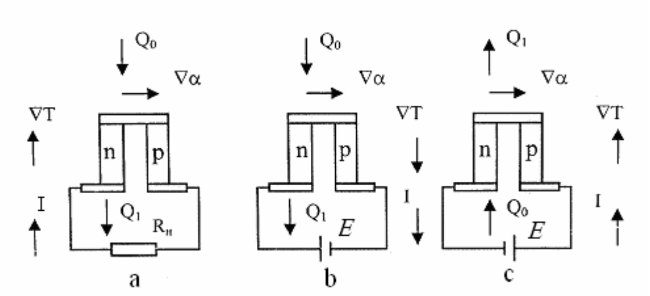

Fig1. The base devices of thermoelectric power industry. a- TEG; b- TEC; c- TEH (E- energy source, R_n- external load, Q_0 and Q_1- input and output heat flows, ∇T and $\nabla\alpha$- gradients of T and α).

The well-known "thermoelectric boom" in 1950 – 1970 was accompanied by general crisis in thermoelectric materials science. The figures of merit $Z = \alpha^2/(\rho k)$ (here α is Seebeck coefficient, $\rho = \sigma^{-1}$ and σ are the partial resistance and conductance, k is thermal conductivity) for all thermoelectrics approached their superior limit.

So to enhance the performance one used cascading of the devices (up to III- stage and more) and segmentation and grading of the legs [3]. TEG, where the temperature drops along the legs attained $\Delta T \sim 300$ K and more, were the first on this way [3,4]. A.F.Ioffe give rise some rules for choice the well-matched thermoelectric materials for cascade TEG [3]. One of them is to use the materials of ultimate Z_{max} (T) in different cascades and segments for maintenance of optimum value $\alpha \sim 172$ μV/ K by length. So the carrier density (n, p) along the length of leg should be increased in the hot zone. The rule [3] prevents TEG from intrinsic conduction, but it is failured for segmented TEC [5-6].

According to [5-6], the drop of ΔT in segmented TEC may be increased, when the high carrier density (n, p) segments are in the *cold* zone. This violent discrepancy to rule [3] was attributed to DPE perturbation in legs [5-6].

Now the theory of DPE is essentially developed that one enable to do the optimal design of graded legs [1,4]. The methods for inhomogeneous legs formation were completed (Table 1).

Table 1

Some methods for inhomogeneous legs formation

Methods		Ref
Technological	Segmented legs	[3]
	Graded legs	[3]
Heterogenous external effects	Mechanical stresses	[7]
	Magnetic fields	[7]
«Spontaneous» effects in working module	α versus T dependences: a) extrinsic conduction b) intrinsic conduction	[6,8] Present work
	Thermal diffusion of the fast ions (Cu, Ag so on)	[9]

The purpose of the present work was to study the contributions of the "bulk" effects (DSE and DPE) in enhancing the performance of TED with inhomogeneous legs based on bismuth and antimony chalkogenides (BAC) (Fig.1). The common rule was developed for the proper sets of inhomogeneous legs in TEG, TEC and TEH. The physical mechanisms and perspective of applications of distributed effects in power industry were studied.

General theoretical analysis

Our first step was to determine the proper sets for inhomogeneous legs in TEG, TEC and TEH (Fig.1). This problem was successfully solved by using the standard theory of heat balance and the simple leg model with two segments [1]. We obtained the expressions for the base parameters of TEG, TEC and TEH with 2- segment legs [10]. As a rule the expressions obtained transformed to standard ones and back under exchange $\alpha T \leftrightarrow \alpha' T \pm C_i \Delta\alpha T^*$, here α and α' are the contact drops of Seebeck coefficient in standard and segmented legs, T and T* are the temperatures on the top of the device and at intersegment boundaries, $C_i \sim 0$- 1 are the coefficients, depending on intersegment boundaries position, the signs (±) account for enhancing the performance and degradation of devices accordingly.

The proper orientations of $\nabla\alpha$ and I in inhomogeneous legs that enhance the performance of the devices is shown in Fig.1. We deduced the general rule for proper set of legs in different devices (Fig.1). **For TEG and TEC one should set inhomogeneous legs as a cooler ($\nabla\alpha \uparrow\uparrow$ I), and for TEH – as a heater ($\nabla\alpha \uparrow\downarrow$ I).** In terms of “cold” and “hot” zone *the rule* looks as it is presented in Table 2.

Table 2.

The proper orientation of inhomogeneous legs in the devices

Device	Cold zone	Hot zone
TEG	Low (n, p) (high /α /)	High (n, p) (low /α /)
TEO	High (n, p) (low /α /)	Low (n, p) (high /α /)
TEH	Low (n, p) (high /α /)	High (n, p) (low /α /)

That is to say, the high carrier concentrations (n, p) sides of legs should be placed at the top of devices (Fig.1). *The rule* is in accordance with thermodynamical principle of Le Chatelier-Braun and was confirmed by our latter tests.

Using *the rule* by the slope of curves $\alpha = f(T)$ for BAH [1], we had estimated the contributions of Thomson effect ($\nabla\alpha_T$) to efficiency of the devices (Table 3).

Table 3

Thomson effect contributions to the efficiency of device for extrinsic/ intrinsic conduction area of the leg materials (BAH).

Device	$\nabla\alpha_T$ versus I orientation	The performance enhance
TEG	$\nabla\alpha \uparrow\downarrow$ I / $\nabla\alpha \uparrow\uparrow$ I	- / +
TEO	$\nabla\alpha \uparrow\uparrow$ I / $\nabla\alpha \uparrow\downarrow$ I	+ / -
TEH	$\nabla\alpha \uparrow\downarrow$ I / $\nabla\alpha \uparrow\uparrow$ I	- / +

From Table 3 one can see that Thomson effect enhance the performance of TEC in extrinsic conduction area as described previously [6,8], but for TEG and TEH in intrinsic conduction one that is of practical interest (Table 1).

With *the rule* we hold the proper leg sets in our experiments and calculations.

Numerical calculations

The software for calculating the main parameters of I-, II- and III- stage devices (Fig.1) with 2- segment legs in the temperature range of 100 to 400 K was developed with consideration for the temperature dependences of thermoelectric properties of materials and the asymmetry of the segments length and the heat losses on the hot and cold junctions of each cascade.

The imput parameters for calculations were derived from our previous measurements of temperature dependencies of α, σ, and κ for BAH alloys [10-12]. The modules were designated by room temperature Seebeck coefficient $\alpha_{300\ K}$ of segments used in the legs. The results are presented in Fig.2 to 4 and in Table 4 to 5. Calculations show the possible improvement of performance for all devices.

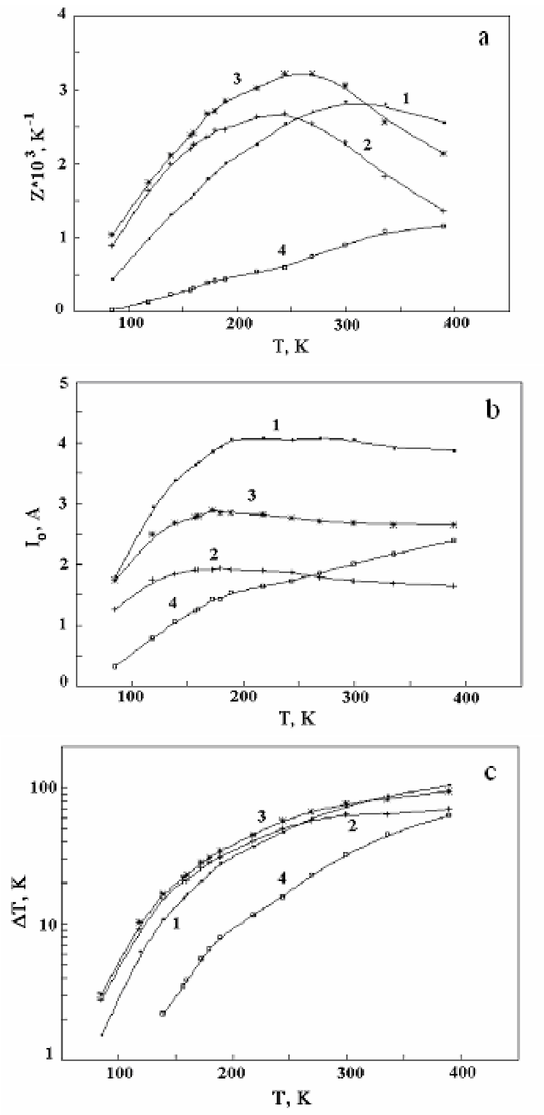

Fig.2. Calculations of figure of merit Z (a), optimal current I_0 (b), and temperature drop ΔT_{max} (c) for TEC. Modules: 1- (187/-185); 2- (268/-270); 3, 4 – (268/187/-185/-270). The leg sets: 3- ($\nabla\alpha \uparrow\uparrow$ I); 4- ($\nabla\alpha \uparrow\downarrow$ I).

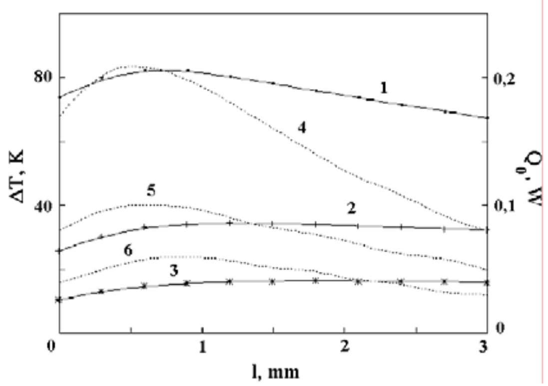

Fig.3. Calculations of the temperature drop ΔT_{max} (1-3) and cold production Q_0 (4-6) dependencies on high resistant segment length l. Modules: 268/156/-171/-270. T, K: 1, 4- 300; 2, 5- 220; 3, 6- 140.

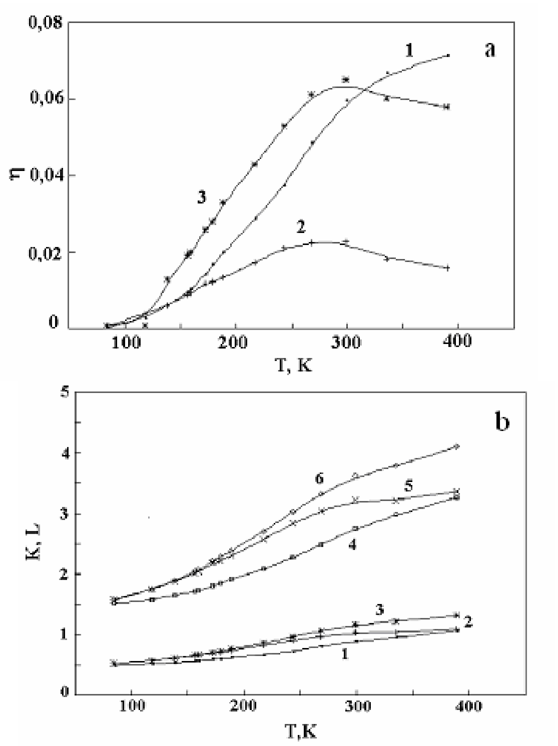

Fig.4. Calculations of the efficiency η for TEG (a), cooling K and hitting L coefficients for TEC and TEH (b). Modules: 1,4- (187/-185); 2,5- (268/-270); 3,65 – (268/187/-185/-270. ΔT, K: 1- 3 (b)- 60; 4-5(b)- 20.

Table 4.

Calculations of the numder of thermocouples in stage for I-, II- and III-stage TEC with homogeneous and inhomogeneous legs (zero heat losses)

Thermocouple	Numder of thermocouples in stage		
187/-185	4	10	59
268/-270	4	9	58
268/187/-185/-270	4	10	60
Number of stages	I	II	III

Table 5.

Calculations of the temperature drop ΔT_{max} for I-, II- and III- stage TEC (4-10-60) with homogeneous and inhomogeneous legs (zero heat losses)

Thermocouple	Temperature drop ΔT_{max},K		
187/-185	74	99	114
268/-270	63	85	97
268/187/-185/-270	83	111	128
Number of stages	I	II	III

Experimental

We examined 2- segment, graded and homogeneous legs cut from special grown homogeneous and inhomogeneous BAH single crystals of different compositions [10-12]. For measurements we used modules, consisting of 2 thermocouple (1,4x1,4x2,5 mm^3) [12]. The measurements were carried out in the temperature range of 90 to 350 K under remanent pressure in cryostat 1 Pa for TEC and 10 Pa for TEG and TEH. The accuracy of measurements was: for T ~ 0, 5 K, for ΔT ~ 0, 1 K, for U and $\alpha_{300\ K}$ ~ 3%. The results, obtained for graded module (260/200/-200/-260) in comparision with homogeneous ones (200/-200) and (260/-260) set as are presented in Fig. 5 to 6. Modules were swiched on as TEG, TEC, and TEH in turn.

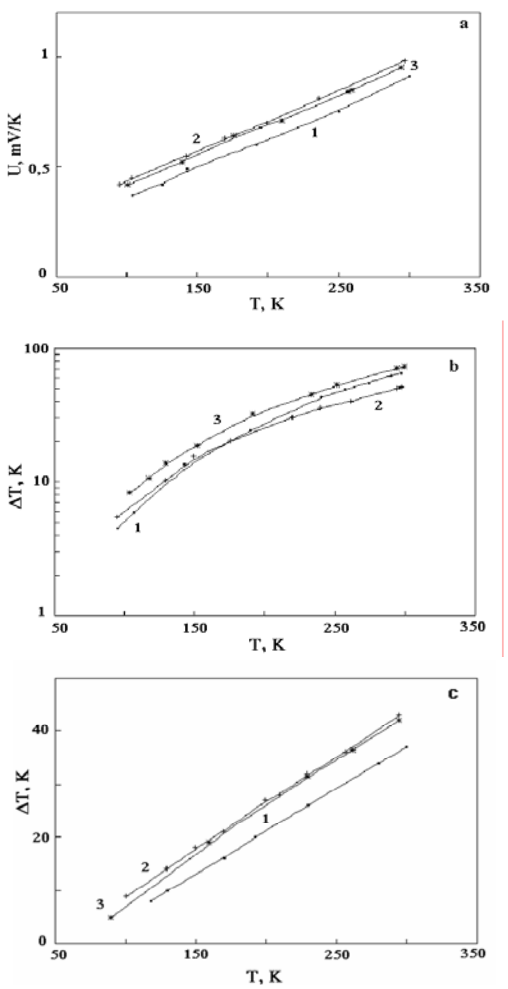

Fig.5. Experimental voltage U for TEG (a), the temperature drop ΔT_{max} for TEC (I= I_o) (b) and for TEH (I= 0,8 A) (c). Modules: 1- (200/-200); 2-(260/-260) ; 3- (260/200/-200/-260).

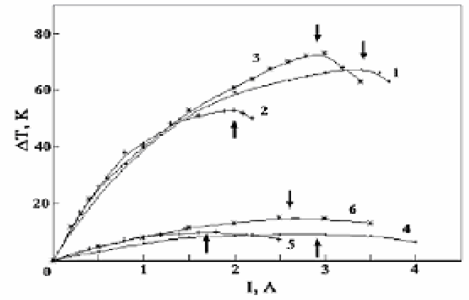

Fig.6. Experimental ΔT_{max} versus I dependencies for TEO. Modules: 1, 4 - (200/-200); 2, 5 – (260/-260); 3, 6 - (260/200/-200/-260). T, K: 1, 2, 3 – 300; 4, 5, 6 – 130. Arrows show I_0 positions.

The experimental results were in agreement with the calculation that help us in comprehensive analysis of the phenomena.

Discussions

Now we are ready to solve the discrepancy [3] and [5,6] mentioned above. It follows from Fig.1 and Fig.2 (curve 3, 4) that proposal [3] is valid for TEG, but support the improper leg sets for TEC. So using the proper inhomogeneous leg sets (Fig.1, Table 2) one can enhance the performance of TEG and TEH (Fig.4) as well as TEC [5,6] .

At room temperature the drop of ΔT_{max} for I-, II- and III-stage TEC (Fig. 2, c, Fig. 5, b, Table 5), the cooling coefficient Κ for TEC and the hitting coefficient L for TEH (Fig.5, b), as wel as the efficiency η for TEG (Fig.5, a) are 1.15- 1.3 time more in comparision with ones of the high conductive segments of legs being optimal at 300 K (curve 1, Fig.2, a). When the temperature decrease the low conductive segments of legs become optimal (curve 2, Fig.2, a) and one can see the ongoing enhance the performance (Fig. 2 to 5). At the high temperature the intrinsic conductions occurred in BAH [1] and the advantage of inhomogeneous legs falls (curves 3, Fig.2, a, c), Fig 5, a, Fig. 7, b) in accordance with the falls of properties of low conductive segments of the legs (curves 2, ibid).

Generaly speaking, the enhance the performance of devices (Fig.1) is due to increasing the effective figure of merit Z* in segmented modules in comparision with Z_1 and Z_2 of homogeneous ones (Fig.2, a). In agreement with [5,6], we obtained that Z* increase is proportional to $/\Delta\alpha/$ drop along the leg so one should increase $\Delta\alpha$ to enhance DSE and DPE contributions. From the other hands, the increase of $\Delta\alpha$ give rise the intrinsic conductions in the legs that in turn decrease Z* (curve 3, Fig.2, a).

In extrinsic conductivity area Z* is the envelope curve for Z_1 and Z_2, Z^*_{max} being situated between Z_{max1} and Z_{max2} (Fig 2, a). As Z_{max1} and Z_{max2} are pined to temperature scale one could not vary the position and magnitude of Z* as easy as for homogeneous legs. But Z* may be optimized by decrease the length l of high conductivity segments (Fig.3) [1,5,6]. We deduce that the legs were optimized due to the corresponding increase of I_0 (Fig. 2, b), that give rise Z* increase in segmented modulus.

The increase of temperature drop ΔT_{max} for segmented TEC (curves 3, Fig.2, a) is due to the corresponding increase of I_0 (curves 3, 6, Fig.6) in comparision with the low conductive modules combined with the high slope of $(\alpha'+\Delta\alpha') \sim \alpha$ (here α is Seebeck constant drop of high conductive modulus) (curves 1, 3, Fig.6). Relation $(\alpha'+\Delta\alpha') \sim \alpha$ explaines the other curves of Fig. 6 as well.

For multistage thermoelectric devices we detected no differences in desigh (Table 4), but some new problems were revealed. They are the increase of the heat losses due to influence of intersegment boundaries, the asymmetry of the heat losses at the hot and the cold junctions of each stages [10], the difference in commutation ability of high and low conductivity ends of leg, the height of legs (~1 mm) in multistage devises is the *difficult size* for graded legs, and so on. All the problems mentioned above seems to be solvable.

In conclusion we are going to evaluate the economical range of serial production of modules with inhomogeneous legs. Using our experience in pilot production of modules [10-12], we conclude that man-hours for production of modulus with segmented and graded legs are of 2 to 2,5 time more and the outcome is of 0,05 to 0,7 time less than for modulus with homogeneous legs. Hence it is clear, why the segmented and graded modules of TEC and TEH are not in practice use now [6]. We consider that for increase of DSE and DPE use in thermoelectric applications one should apply the "spontaneous" methods for inhomogeneity formation.

Conclusions

The inhomogeneous legs may be recommended for use in unique one- and multistage thermoelectric devices (TEG, TEC, and TEH) as well as for further fundamental investigations. The use of inhomogeneous legs in serial production of TEC and TEH seems to be practicable under the application of "spontaneous" methods for inhomogeneity formation.

Acknowledgments

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