The Power Increase of Thermoelectric Heaters with Inhomogeneous Legs

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Abstract

The power increase of thermoelectric heaters (TEH) with inhomogeneous legs are examined once more by theoretical and experimental technique to reveal physical mechanism and perspective of applications of the devices in space heating and wast- heat utilization.

Introduction

The use of inhomogeneous legs in thermoelectric energy transducers (TET) was shown to improve (up to 10- 20%) the of thermoelectric generators (TEG) [1] and coolers (TEC) [2,3], both due to the contributions of distributed thermoelectric effects (DTE). Now the calculations of TEG & TEC are deeply worked out to enable the design of modules with functionally graded legs [4-7].

To reverse the electric current I one can transform TEC into TEH, but the similar studies for TEH with inhomogeneous legs seems to be not on a level. Particularly, the design features of inhomogeneous legs for TEH were not exactly specified in comparison with TEG & TEC.

However, TEH are singled out from the other TET due to their excellent power characteristics (Table 1).

Table 1

The typical ranges for basic power characteristics of different devices

Device	Basic power characteristics	Range	Temperature drop, ΔT, K	Ref.
TEG	Efficiency, η	<0,1- 0,2	400-800	[4,6]
TEC	Cooling coefficient, K	∞ 2,3 1,2 0	0 15 25 ΔT_c	[4,7]
TEH	Heating coefficient, L	∞ 3,3 2,2 1	0 15 25 ΔT_c	[4,7]

Here:

$$\eta= A/ Q_1= (\Delta T/ T_1) (M-1)/ (M- T_0/ T_1), \quad (1)$$

$$K= Q_0/ A = (T_0/ \Delta T) (M- T_0/ T_1)/ (M+1), \quad (2)$$

$$L= Q_1/ A= (T_1/ \Delta T) (M- T_0/ T_1)/ (M+1), \quad (3)$$

$A= (Q_1 - Q_0)$ is the work of current I, Q_1 and Q_0 are the heat emission and absorbtion at cold and hot sides of thermocouples respectively,

$$\Delta T_c = ½ Z T_1^2 \quad (4)$$

is the maximum temperature drop for TEC, $M= (1 + Z(T_0 + T_1)/ 2)^{1/2})$, Z is the figure of merit for the device, T_0 and T_1 are the temperatures at the base and at the top of modules (fig.1) [1,4].

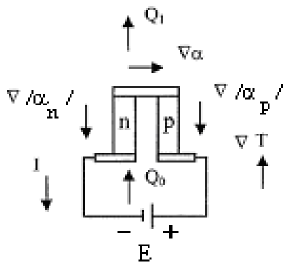

Fig 1. The thermocouple (n/ p) with inhomogeneous legs in TEH. Here E is the d.c. battery, Q_0 and Q_1 are input and output heat flows, ∇T, $\nabla\alpha$ and $\nabla/\alpha_{n,p}/$ are the gradients of T, α and the absolute values of $\alpha_{n,p}$.

There are two significant relations, that follow from expressions (1) to (3) and Table 1:

$$L= K+1> K >> \eta , \quad (5)$$

$$L > 1, \text{ for } \Delta T < \Delta T_c . \quad (6)$$

Relation (5) is due to inverse contributions of Carnot factor (ΔT / T) to "heat pumps" TEC & TEH in comparison with TEG and show it is the TEH, that have preference measure for the energy transformations [1,4]. Inequality (5) is an attribute of thermoelectric heating (in comparison with for Joule heating, for which $L \leq 1$). It does act as TET being an open thermodynamical systems, so Q_1 can exceed A due to "heat pumping" from environment [1]. For this reason the use of inhomogeneous legs for power increase in TEH is the matter of great concern.

Recently we deduced the rules for proper sets of legs in TET - one should set inhomogeneous legs in TEG & TEC as a cooler ($\nabla\alpha$ ↑↑ I), and in TEH – as a heater ($\nabla\alpha$ ↑↓ I). (here $\nabla\alpha= \delta\alpha/\delta x$ is the space gradient of α in n- and p- legs, I is the electric current vector). For all TET vector $\nabla /\alpha_{n, p}/$ of the legs should be directed from the top to the base of the devices (fig.1) [8].

Now we examine TEH with inhomogeneous legs once more by theoretical and experimental technique to reveal the upper limit of performance and the design features of inhomogeneous legs for TEH. The observed increase of heating coefficient L for TEH with inhomogeneous legs in comparison with homogeneous ones was of 20% (starting temperature T= 300 K, hitting range ΔT= 20- 30 K), that is of major practical interest for domestic heating.

Experimental

We examined 2- thermocouples modules (Fig.2) with homogeneous high-resistance (260/-260), low-resistance (200/-200), and graded inhomogeneous legs (260/200/-200/-

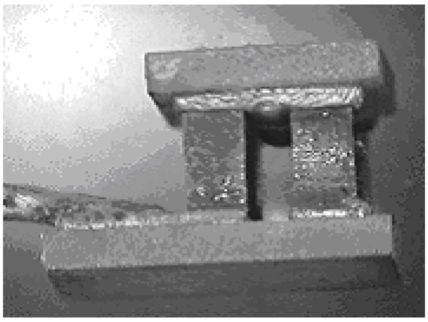

Fig 2. Standard 2- thermocouples modulus used in our experiments.

260) in comparison to each other (Table 2). The modules were designated by room temperature Seebeck coefficient $\alpha_{300\ K}$ of legs and segments. The legs for modules were of the same size (1,4x1,4x2,5 mm^3) being cut from special grown homogeneous and inhomogeneous bismuth and antimony chalkogenides (BAC) single crystals of different compositions [8-11].

Table 2

The experimental room temperature characteristics of modules.
1 - (200/-200); 2- (260/-260); 3-(260/200/-200/-260).

№	Total Seebeck coefficient drops, Δα, μV/K	Total resis-tance R, Ohm	Heat conducti-vity, $K*10^3$, W/ K	Figure of merit, $Z*10^3$, 1/ K	Cooling items, ΔT_c,K/ I_0, A	Starting heating slop, ΔT_h/ I, K/ A
1	400	0,035	4,86	2,6	68/ 2,9	25
2	520	0,166	3,87	2,3	51/ 2,0	42
3	520	0,101	4,32	3,2	75/ 3,5	35

Graded legs with Seebeck coefficient drops $\Delta\alpha_{n,p}$ of 60μV/K occurred at x/l ~ 0,5 were oriented in TEH in accordance with Fig.2. The measurements were carried out in the temperature range of 90 to 350 K under remanent air pressure in cryostat < 1 Pa. To get the set of needed characteristics we put on modules into a power line as TEC and TEH in turn. The cooling ΔT_c and heating ΔT_h effects were measured versus operating current I. The accuracy of measurements was: T ~ 0, 5 K, ΔT ~ 0, 1 K, I~ 1%.

Numerical calculations

For numerical calculations we used the model with 2-segmented legs, the inter-segment boundaries within the legs being mobile (x/l= [0-1]) (Fig.3). The results for homogeneous high-resistance and low-resistance legs were obtained for x= 0 and x= 1 respectively.

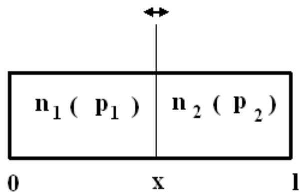

Fig 3. The model of 2-segmented legs with the mobile inter-segment boundary.

The imput parameters for calculations were derived from previous measurements of temperature dependencies of Seebeck coefficient α, partial electric conductivity σ =1/ρ (here ρ is the partial electric resistivity) and heat conductivity κ, all attributed to corresponding BAC alloys [8-9]. Using 2- segmented model (Fig.2), we derived the expressions (7 to 10) for the main parameters of TEC & TEH with inhomogeneous legs [9]:

$$\Delta T_c \cong (\bar{\alpha}\, T_1 \pm C^*\Delta\alpha\, T^*)^2 / 2KR, \qquad (7)$$

$$I_0 \cong (\bar{\alpha}\, T_1 \pm C^*\Delta\alpha\, T^*) / R, \qquad (8)$$

$$\Delta T_h \cong ((\bar{\alpha}\, T_1 \pm C^*\Delta\alpha\, T^*)\, I + \tfrac{1}{2} I^2 R) / K, \qquad (9)$$

$$I_{max} \cong (\bar{\alpha}\, T_1 \pm C^*\Delta\alpha\, T^*)\, \Delta T_h\, M / ((M+1)R). \qquad (10)$$

(here I_0 and I_{max} are the currents of ΔT_c and L maxima accordingly, $\bar{\alpha}= (\alpha_p - \alpha_n)$ and $\Delta\alpha= \Delta\alpha_n + \Delta\alpha_p$ are the Seebeck coefficient drops at p-n- junction and at segment boundaries, T* is the temperature of segment's boundaries, C* ~ 0- 1 are the calculated coefficients, depending on inter- segment boundaries position (C*= 0 for homogeneous legs), the signs (±) account for enhancing or reduction the performance of devices for proper and improper leg's sets accordingly, R и K are the effective electrical resistance and the heat conductivity of the legs). Using the expressions (3), (4) and (7), we get the effective figures of merit Z and than heating coefficient L for modules. The T* values were calculated by joint interpolation followed by iteration refinement.

Experimental Results and Discussion.

The experimental results obtained for modules (Table 2) are presented in Fig.4 and Fig.5. From Fig.4 one can see that

$$\Delta T_h\ (2) \geq \Delta T_h\ (3) > \Delta T_h (1). \qquad (11)$$

So under the condition *I- const* the inhomogeneous modulus slightly reduce ΔT_h in comparison with homogeneous high-resistance ones being of the same total Seebeck coefficient drops (Table 2).

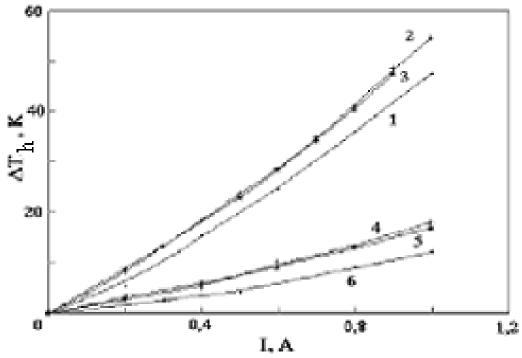

Fig.4. Experimental curves of temperature drop ΔT_h versus current I for TEH. Modules: 1, 6- (200/-200); 2, 4- (260/-260); 3, 5 - (260/200/-200/-260).
Base temperature T_0, K: 1, 2, 3 – 300; 4, 5, 6 – 130.

Contrary to (11), heating coefficients L (Fig.5), attained at optimum currents I_{max} of modules, show the relation

$$L(3) > L(2) > L(1). \quad (12)$$

So under I_{max} the inhomogeneous modulus (260/200/-200/-260) is ~20 % enhanced as compared to the best homogeneous high-resistance one.

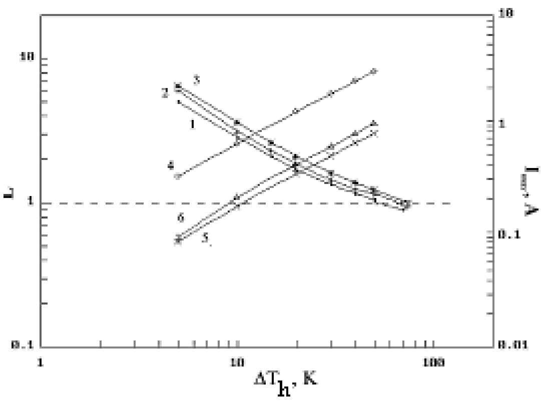

Fig.5. Heating coefficient L (1-3) and optimum current I_{max} (4-6) versus temperature drops ΔT_h for TEH (T_0= 300K). .Modules: 1, 4- (200/-200); 2, 5- (260/-260); 3, 6 - (260/200/-200/-260).

The experimental results obtained for TEH are in agreement with the our calculations. Using expression (9) and taking into account the differences of the total Seebeck coefficient drops $\Delta\alpha$ and heat conductivities K for modules (Table 2) as well as the inequality $T^* < T_1$ one can explain the relation (11). The drastic increase of heating coefficient L for inhomogeneous modulus (260/200/-200/-260) (Fig.5) one can attribute to the corresponding increase of figure of merit Z (Table 2).

We deduced that the power increase for TEH as well as for TEG & TEC with inhomogeneous legs in comparison with homogeneous ones is due to the relative decrease of irreversible processes contribution (Joule's heat emission and heat conductivity) at leg's symmetry disturbance.

It will be noted, that the legs of the same size with inter-segment boundaries at x/l= 0,5, used for comparison of modules in present paper, are not optimal. To derive the maximum L one should optimize the position of inter-segment boundaries within the legs and get a good match for cross- sections of legs according to condition

$$S_1/ S_2= (k_1 \rho_2 / k_2 \rho_1)^{1/2}, \quad (13)$$

here S_1 and S_2 are the cross- sections of the legs [1,2].

The results of optimization of the inter-segment boundaries position within the legs for our modules are presented in Table 3, the same kind of thing for cross-sections of segments & legs are shown in Table 4..

Table 3

Calculated figures of merit Z versus relative length of high-resistance segments for modulus (260/200/-200/-260)

x_1/l	0	0,25	0,33	0,5	1,0
$Z*10^3$, 1/K	2,9	3,4	3,4	3,2	2,5

Table 4

Optimized relative cross- sections of segments & legs

Modules	p_1	p_2	n_1	n_2	Losses in δZ, %
(260/-260)	1	-	0,68	-	2
(200/-200)	-	1	-	0,80	4
(260/200/ -200/-260)	1	0,5	0,77	0,43	16

According to Table 3 the best feat for inter- segment boundaries position within the legs for TEH is x/l= 0,25-0,33 as well as for TEG & TEC [2,4]. From Table 4 one can see, that to prevent the losses in Z attributed to the same size the segments & legs, the last should be optimized by their cross- sections. The optimized configurations for well-matched p- and n- segments & legs of thermocouples in questions are present in Fig 6 (darken) .

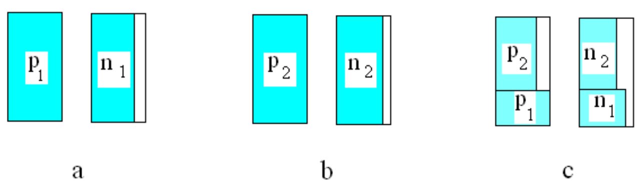

Fig 6. Calculated configurations for well-matched p- and n- legs of thermocouples. a- (260/-260); b- (200/-200); c- (260/200/ -200/-260).

From Tables 3 to 4 and Fig. 6 one can deduced, that by optimization the L increase for inhomogeneous modulus (260/200/-200/-260) may be enlarged in the end up to ~ 35-40%. The enlarged effect of inhomogeneous segments and legs optimization in comparison to homogeneous ones (Table 4) results from the enlarged differences in absolute values of /k/ and /ρ/ for inhomogeneous materials. So we conclude, that cross- sections optimization of segments & legs does required for TEH and for TEG & TEC as well.

In addition we should declare, that power increase for thermoelectric heaters (TEH) with inhomogeneous legs does exist and being large as well as for TEG & TEC ones [1-4]. It is suggested that this effect may be successfully used for solving the problems of space heating, waste-heat energy utilization, climate control and so on [12]. In despite of TEH's excellent power characteristics ((5) to (6)), at the same time there are some "reefs" on this way including economical restrictions. The economical range of different modules production based on our experience in pilot assembling of modules [8-11] is present in Table 5.

Table 5

The economical range of different modules production.

Manufacturing methods	Relative man-hours for production of modulus		
	Homogeneous	Segmented	Graded
Crystal growth	1	~2	~1,3- 1,5
Cutting of legs	1	~3- 4	~2- 3
Mounting cost	1	~1,5	~2
Optimization	1	~2- 3	~3- 5
Yield	0,6- 0,7	~0,4- 0,5	~0,02- 0,04

According to Table 5, there is drastic increase of man-hours for production of modulus with inhomogeneous (segmented and graded) legs. So it is clear, why the segmented and graded legs are not in common use now [6]. We consider that for increase of DTE use in thermoelectric applications one should apply the "spontaneous" methods for inhomogeneity legs formation (magnetic fields H applications, α versus T dependences, thermal diffusion of the fast ions (Cu, Ag) and so on) [5,7-10].

Conclusions

As a result of investigation we deduced that: 1) the general rule for proper set of inhomogeneous legs in TEH is: $\nabla\alpha\uparrow\downarrow$ I, that is contrary to TEG & TEC ($\nabla\alpha\uparrow\uparrow$I); 2) the rules for inter- segment boundary position (x/l~ 0,25-0,33) and cross- sections of segments & legs optimization in TEH is the same as in TEG & TEC; 3) the observed increase of heating coefficient L for TEH with inhomogeneous legs in comparison with homogeneous ones was of 20% (starting temperature T= 300 K, hitting range ΔT= 20- 30 K), there is the reserve of L enhance up to ~ 35- 40% by optimization, that is of major practical interest for domestic heating; 4) the power increase for all the TET with inhomogeneous legs is due to the relative decrease of irreversible processes contribution (Joule's heat emission and heat conductivity) at leg's symmetry disturbance; 5) the use of inhomogeneous legs in serial production seems to be practicable only under the application of "spontaneous" methods for inhomogeneity formation.

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