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 waste-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

<table>
<thead>
<tr>
<th>Device</th>
<th>Basic power characteristics</th>
<th>Range</th>
<th>Temperature drop, ∆Τ, K</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG</td>
<td>Efficiency, η</td>
<td>&lt;0,1-0,2</td>
<td>400-800</td>
<td>[4,6]</td>
</tr>
<tr>
<td>TEC</td>
<td>Cooling coefficient, K</td>
<td>∞</td>
<td>0</td>
<td>[4,7]</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>∆Τ₉₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEH</td>
<td>Heating coefficient, L</td>
<td>∞</td>
<td>0</td>
<td>[4,7]</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>∆Τ₉₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Here:

\[ η = \frac{A}{Q_1} = (\frac{∆Τ}{T_1})(M-1)/(M-\frac{T_0}{T_1}), \]  

\[ K = \frac{Q_0}{A} = (\frac{T_0}{∆Τ})(M-\frac{T_0}{T_1})(M+1), \]  

\[ L = \frac{Q_1}{A} = (\frac{T_1}{∆Τ})(M-\frac{T_0}{T_1})(M+1), \]

\[ A = (Q_1 - Q_0) \] is the work of current I, and \( Q_1 \) and \( Q_0 \) are the heat emission and absorption at cold and hot sides of thermocouples respectively.

\[ ∆Τ₂ = \frac{1}{2} Z T_1^2 \] \hspace{1cm} (4)

is the maximum temperature drop for TEC, \( M = (1 + Z(\frac{T_0}{t} + T_1)/2)^{1/2} \), \( Z \) 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].

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

\[ L > 1, \quad \text{for} \quad ∆Τ < ∆Τ₂. \] \hspace{1cm} (6)

Relation (5) is due to inverse contributions of Carnot factor \((∆Τ / T)\) 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 (\( ∇α \uparrow \downarrow I \)), and in TEH – as a heater (\( ∇α \uparrow \downarrow I \)). (here \( ∆α = \delta α / δx \) is the space gradient of \( α \) in n- and p-legs, \( I \) is the electric current vector). For all TET vector \( ∇/α_{n,p} \) 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
in comparison with homogeneous ones was of 20% (starting temperature $T=300$ K, hitting range $\Delta T=20$–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 $(260/200/-200/-260)$ in comparison to each other (Table 2). The modules compositions \[8-11\].

![Fig 2. Standard 2-thermocouples modulus used in our experiments.](Image 89x525 to 247x642)

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

The input parameters for calculations were derived from previous measurements of temperature dependencies of Seebeck coefficient $\alpha$, partial electric conductivity $\sigma=1/\rho$ (here $\rho$ is the partial electric resistivity) and heat conductivity $\kappa$, 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]:

\[
\Delta T_c \approx \left( \frac{\bar{\alpha} T_1 \pm \Delta \alpha T^*}{2} \right)^2 / 2KR, \\
I_0 \approx \left( \frac{\bar{\alpha} T_1 \pm \Delta \alpha T^*}{R} \right), \\
\Delta T_h \approx \left( \left( \frac{\bar{\alpha} T_1 \mp \Delta \alpha T^*}{1/2} \right)^2 \frac{R}{K} \right), \\
I_{\text{max}} \approx \left( \frac{\bar{\alpha} T_1 \pm \Delta \alpha T^*}{M/\left(M+1\right)R}. \right)
\]

(here $I_0$ and $I_{\text{max}}$ are the currents of $\Delta T_c$ 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, $C^* \sim 0$ - 1 are the calculated coefficients, depending on inter-segment boundaries position ($C^* = 0$ for homogeneous legs), the signs ($\pm$) account for enhancing or reduction the performance of devices for proper and improper leg’s sets accordingly, $R$ u $K$ 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.

Experiments 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

\[
\Delta T_h \left(2\right) \geq \Delta T_h \left(3\right) \geq \Delta T_h \left(1\right).
\]

So under the condition $I-\text{const}$ the inhomogeneous modulus slightly reduce $\Delta T_h$ in comparison with homogeneous high-

Table 2

<table>
<thead>
<tr>
<th>№</th>
<th>Total Seebeck coefficient drops, $\Delta \alpha$, $\mu$/K</th>
<th>Total resistance, $R$, Ohm</th>
<th>Heat conductivity, $\kappa$, W/K</th>
<th>Figure of merit, $Z$, $10^3$</th>
<th>Cooling items, $\Delta T_h$, K/ A</th>
<th>Starting heating slope, $\Delta T_h$, I, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
<td>0.035</td>
<td>4.86</td>
<td>2.6</td>
<td>68/2.9</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>520</td>
<td>0.166</td>
<td>3.87</td>
<td>2.3</td>
<td>51/2.0</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>520</td>
<td>0.101</td>
<td>4.32</td>
<td>3.2</td>
<td>75/3.5</td>
<td>35</td>
</tr>
</tbody>
</table>

Graded legs with Seebeck coefficient drops $\Delta \alpha_{np}$ of $60\mu$/K occurred at $x/l \sim 0.5$ 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 $\Delta T_c$ and heating $\Delta T_h$ effects were measured versus operating current I. The accuracy of measurements was: $T \sim 0$, 5 K, $\Delta T \sim 0$, 1 K, $I \sim 1\%$. 

\[
\Delta T \sim 0, 5 K, \Delta T \sim 0, 1 K, I \sim 1\%.
\]
resistance ones being of the same total Seebeck coefficient drops (Table 2).

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

$$L(3) > L(2) > L(1).$$

(12)

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

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

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

(13)

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

The results of optimization of the inter-segment 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.

The experimental results obtained for TEH are in agreement with 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).
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 $\kappa$ and $\rho$ 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

<table>
<thead>
<tr>
<th>Manufacturing methods</th>
<th>Relative man-hours for production of modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Homogeneous</td>
</tr>
<tr>
<td>Crystal growth</td>
<td>1</td>
</tr>
<tr>
<td>Cutting of legs</td>
<td>1</td>
</tr>
<tr>
<td>Mounting cost</td>
<td>1</td>
</tr>
<tr>
<td>Optimization</td>
<td>1</td>
</tr>
<tr>
<td>Yield</td>
<td>0,6-0,7</td>
</tr>
</tbody>
</table>

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, $\alpha$ 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: $\kappa\alpha^{\uparrow\uparrow\uparrow}$ I, that is contrary to TEG & TEC ($\kappa\alpha^{\uparrow\uparrow}$ I); 2) the rules for inter- segment boundary position ($x\approx0.25-0.33$) 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 $\Delta T=20-30\ K$), 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.

Acknowledgments

We thanks Dr. Ivanova L.D. and Dr. Svechnikova T.C. for BAC supply, Russian Basic Research Foundation for financial support (Grant №06-08-00084).

References