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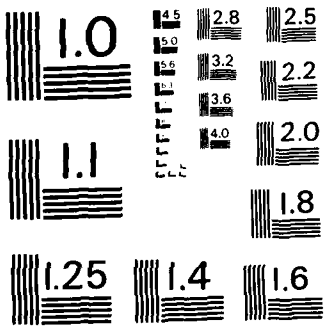

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FOREIGN TECHNOLOGY DIVISION

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EFFECTIVE PARAMETERS OF A CASCADE THERMOPILE

by

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FOREIGN TECHNOLOGY DIVISION

85 12 17 118

EDITED TRANSLATION

FTD-ID(RS)T-1114-85 18 Nov 85

MICROFICHE NR: FTD-85-C-001118

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English pages: 7

Source: Izvestiya Akademii Nauk SSSR, Energetika i Transport, Nr. 6, November-December 1969, pp. 137-140

Country of origin: USSR
Translated by: Charles T. Ostertag, Jr.
Requester: FTD/TQTD
Approved for public release; distribution unlimited.

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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EFFECTIVE PARAMETERS OF A CASCADE THERMOPILE

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Submitted 9 Jan 1969

For the description of the working characteristics of a multicascade thermopile equations are proposed which are simple in their mathematical structure, and in which the physical properties of the individual cascades are replaced by effective parameters, giving a concept about the properties of the chain of cascades as a whole.

Calculation formulas are given for the calculation of effective parameters based on the results of tests of a cascade thermopile. The physical meaning of the effective parameters is discussed and their interconnection with the properties of the individual cascades is shown. References 3, pages 136-139.

Formulation of the problem. The calculation processing of experimental data, obtained in the testing of thermoelectric devices, amounts mainly to the finding of the physical parameters, which would determine sufficiently completely the thermoelectric properties of the investigated object (thermopile, thermoelement or thermal battery). As is known [1], for a homogeneous thermopile such determining parameters are the magnitudes, averaged over the working range of temperatures, of thermal resistance k, electric resistance r, and specific thermal emf α . The experimental values of the determining parameters are usually calculated stemming from the equations of heat balance on the hot and cold junctions of the thermopile

$$q_r = (T_r - T_x)\,k + j\alpha T_r - j^2 r/2, \qquad (1)$$

$$q_x = (T_r - T_x)\,k + j\alpha T_x + j^2 r/2 \qquad (2)$$

and the equation of balance of voltage

$$v = \alpha(T_r - T_x) - jr, \qquad (3)$$

where j - force of electric current, v - voltage on the ends of the thermopile, T_r and T_x - temperatures of the hot and cold junctions, q_r and q_x - flows of heat on the hot and cold junctions.

Much more complex is the question of the methodical approach to the processing of the results of tests of multicascade thermoelements.

In work [2] an investigation was made of the thermal and electrical interaction of cascades in a multicascade thermopile. It is advisable to use the formulas obtained in this case for the solution of problems, developing in the phase of preliminary designing of thermoelectric devices, when it is required to calculate the energy balance of a cascade thermopile with assigned physical properties (k, r, α) for the individual cascades. However, the attempt to use the same equations for the purpose of describing experimental results, obtained in tests of cascade thermoelements, encounters considerable difficulties. The main source of these difficulties - nonconformity between the complex structure of calculation formulas, taking into account the properties of each cascade separately, and the generally accepted simple (and more convenient from a practical point of view) arrangement of experimental measurements *, giving an idea about the working characteristics of the chain of cascades as a whole.

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* Usually the following measurements are made: electric current j, voltage v, temperatures T_r and T_x of the hot and cold ends, flows of heat q_r and q_x on the hot and cold ends of the thermopile.

Meanwhile the calculation formulas themselves contain the possibilities of their simplification. As we already noted in [2], the output characteristics of multicascade and single-cascade thermopiles differ little from each other in a qualitative respect. This means that in principle it is possible to describe with sufficient accuracy the operation of a multicascade thermopile with approximate formulas, which in their mathematical structure call to mind the known formulas of energy balance for a single-cascade thermopile (1)-(3). For this it is necessary to switch from the physical properties of the individual cascades to effective parameters, characterizing the properties of the chain of cascades as a whole.

Main calculation correlations. Transition to effective parameters is realized by the division of the polynomials in formulas (13)-(14) of work [2], the result of which are the infinite power series from the parameter j. Disregarding the terms of the higher orders of smallness, we obtain the approximate equations of thermal balance on the hot and cold ends of the thermopile

$$q_{\text{г}} \approx (T_{\text{г}} - T_{\text{х}})/k_{\text{эф}} + j\alpha_{\text{эф}} T_{\text{г}} + j\xi_{\text{эф}}(T_{\text{г}} - T_{\text{х}}) - j^2 r_{\text{эф}}(1 + \beta_{\text{эф}})/2, \quad (4)$$

$$q_{\text{х}} \approx (T_{\text{г}} - T_{\text{х}})/k_{\text{эф}} + j\alpha_{\text{эф}} T_{\text{х}} + j\xi_{\text{эф}}(T_{\text{г}} - T_{\text{х}}) + j^2 r_{\text{эф}}(1 - \beta_{\text{эф}})/2 \quad (5)$$

and the equation of balance of voltage

$$v \approx \alpha_{\text{эф}}(T_{\text{г}} - T_{\text{х}}) - j r_{\text{эф}}. \quad (6)$$

The effective parameters for a thermopile, consisting of n series connected cascades, are connected with the physical properties of the individual cascades by the following correlations:

$$k_{\text{эф}} = \sum_{i=1}^{n} k_i, \quad (7)$$

$$\alpha_{\text{эф}} = \sum_{i=1}^{n} \alpha_i k_i / k_{\text{эф}}, \quad (8)$$

$$\xi_{\text{эф}} = \sum_{i_1 < i_2}^{(1,2,\ldots,n)}{}' k_{i_1}(\alpha_{i_1} - \alpha_{i_2}) k_{i_2} k_{\text{эф}}^{-2}, \quad (9)$$

$$r_{\text{эф}} = \sum_{i=1}^{n} r_i + k_{\text{эф}} \lambda T_{\text{ср}} - k_{\text{эф}} (\alpha_{\text{эф}} \xi_{\text{эф}} - \mu/2) \Delta T, \tag{10}$$

$$\beta_{\text{эф}} = \sum_{i=1}^{n} r_i \left(\sum_{m=i+1}^{n} k_m - \sum_{m=1}^{i-1} k_m \right) \Big/ r_{\text{эф}} k_{\text{эф}} - - k_{\text{эф}} (2\alpha_{\text{эф}} \xi_{\text{эф}} - \mu) T_{\text{ср}} / r_{\text{эф}} + k_{\text{эф}} (\lambda/2 + 2\omega - 2\xi_{\text{эф}}^2) \Delta T / r_{\text{эф}}. \tag{11}$$

Here the subscripts i, m denote the sequence numbers of the cascades (reading from the hot end of the thermopile) and for shortening the notations the following designations are introduced:

$$\Delta T = T_{\text{г}} - T_{\text{х}},$$

$$T_{\text{ср}} = (T_{\text{г}} + T_{\text{х}}) / 2,$$

$$\lambda = \sum_{i_1 < i_2}^{(1,2,\ldots,n)} k_{i_1} (\alpha_{i_1} - \alpha_{i_2})^2 k_{i_2} / k_{\text{эф}}^2,$$

$$\mu = \sum_{i_1 < i_2}^{(1,2,\ldots,n)} k_{i_1} (\alpha_{i_1}^2 - \alpha_{i_2}^2) k_{i_2} / k_{\text{эф}}^2,$$

$$\omega = \left[\sum_{i_1 < i_2 < i_3}^{(1,2,\ldots,n)} k_{i_1} (\alpha_{i_1} - \alpha_{i_2}) k_{i_2} (\alpha_{i_2} - \alpha_{i_3}) k_{i_3} \right] \Big/ k_{\text{эф}}^3.$$

Just as in [2], the sign $\sum\limits_{i_1 < i_2 < \ldots < i_\nu}^{(1,2,\ldots,n)}$ indicates that summation is extended to all possible combinations of ν subscripts i_1, i_2, ..., i_ν, proceeding in increasing order and taken among the numbers 1, 2, ..., n.

It is evident that in a particular case, when the specific thermal emf is the same for all cascades ($\alpha_i = \alpha$, i = 1, 2,..., n), the "internal" Peltier effect (liberation or absorption of Peltier heat on the intermediate junctions with the passage of current) is absent. The distribution of temperatures in the thermopile is conditioned only by the interaction of the flow of thermal conductivity and the Joule effect. In this case the mathematical aspects of the problem concerning a cascade thermopile are simplified sharply, and the strict formulas of heat balance - equations (13), (14) of work [2] - coincide in accuracy with equations (4), (5), expressed in terms of effective parameters. In this case

$$\alpha_{эф} = \alpha, \tag{8a}$$

$$\xi_{эф} = 0, \tag{9a}$$

$$r_{эф} = \sum_{i=1}^{n} r_i, \tag{10a}$$

$$\beta_{эф} = \sum_{i=1}^{n} r_i \left(\sum_{m=i+1}^{n} k_m - \sum_{m=1}^{i-1} k_m \right) \Big/ r_{эф} k_{эф}. \tag{11a}$$

Calculation of effective parameters based on experimental data. The structural simplicity of approximate equations of energy balance (4)-(6) makes it possible without particular difficulty to carry out the calculation processing of experimental data in order to determine the effective parameters of a cascade thermopile. In this case, without detriment for the accuracy of the final results, it is possible to be limited to the determination of only four effective parameters: $k_{эф}$, $\alpha_{эф}$, $r_{эф}$, $\xi_{эф}$ and to disregard the dimensionless coefficient $\beta_{эф}$ in view of the insignificance of its influence on the heat balance of the thermopile.

Thus, having available the results of measurement of current j, voltage v, temperatures $T_г$ and $T_х$ of the ends of the thermopile and the thermal power $q_г$ supplied to the hot end in the idling mode (circuits open) and in the mode with a working load, it is possible to calculate the effective parameters of the thermopile using the formulas

$$k_{эф} = \Delta T^{xx} / q^{xx}, \tag{12}$$

$$\alpha_{эф} = v^{xx} / \Delta T^{xx}, \tag{13}$$

$$r_{эф} = (v^{xx} \Delta T^{рн} - v^{рн} \Delta T^{xx}) / j^{рн} \Delta T^{xx}, \tag{14}$$

$$\xi_{эф} = \left[q_г^{рн} \Delta T^{xx} - q_г^{xx} \Delta T^{рн} - j^{рн} \left(v^{xx} T_г^{рн} + \frac{1}{2} v^{рн} \Delta T^{xx} \right) \right] \Big/ j^{рн} \Delta T^{рн} \Delta T^{xx}, \tag{15}$$

where the superscripts xx and $рн$ denote the variables, measured respectively in the mode of idling and in the mode with a working load.

Physical essence of effective parameters. It is not difficult to give a simple physical interpretation to the effective parameters of a cascade thermopile.

The physical essence of the effective thermal resistance $k_{эф}$ is evident - this is the thermal resistance of a multilayer plate, determining the flow of thermal conductivity in the absence of an electric current.

The effective specific thermal emf $\alpha_{эф}$ characterizes the magnitude of the Seebeck effect under the condition that the distribution of temperatures in the thermopile is determined by thermal conductivity.

The parameter $\xi_{эф}$ in a first approximation describes the transfer of Peltier heat, liberated or absorbed on the intermediate junctions in the case of passage of an electric current. Rewriting formulas (4), (5) in the form

$$q_г \approx (T_г - T_х) / k_{эф} + j(\alpha_{эф} + 2\xi_{эф})T_х - j\tau_{эф}(T_г - T_х) / 2 - j^2 r_{эф}(1 + \beta_{эф}) / 2, \quad (4a)$$

$$q_х \approx (T_г - T_х) / k_{эф} + j(\alpha_{эф} - 2\xi_{эф})T_х + j\tau_{эф}(T_г - T_х) / 2 + j^2 r_{эф}(1 - \beta_{эф}) / 2, \quad (5a)$$

it can be accepted formally that the "internal" Peltier effect in a certain sense is analogous to the Thomson effect [3]. Then the variable $(\alpha_{эф} + 2\xi_{эф})T_г$ will correspond to the Peltier coefficient on the hot end, the variable $(\alpha_{эф} - 2\xi_{эф})T_х$ - to the Peltier coefficient on the cold end of the thermopile, and the effective Thomson coefficient for each cascade thermopile will be equal to:

$$\tau_{эф} = 4\xi_{эф} T_{ср} / (T_г - T_х).$$

The effective internal electrical resistance $r_{эф}$ in a general case does not coincide with the true internal resistance $r_{ист} = \sum_{i=1}^{n} r_i$ due to the presence of a correction (coefficients $\xi_{эф}$, λ, μ), taking into account the influence of the "internal" Peltier effect on the field of temperatures in the thermopile, and, consequently, on the actual value of electromotive force which is developed by the cascade thermopile.

The dimensionless coefficient $\beta_{ж}$ indicates the "asymmetric" (in respect to the hot and cold ends) nature of propagation of the liberated Joule heat along the length of the thermopile and also contains the correction for the "internal" Peltier effect.

<u>Conclusions.</u> 1. In place of the precise formulas of the energy balance for a multicascade thermopile the approximate formulas (4)-(6) have been proposed. In these formulas the physical properties on the individual cascades have been replaced by effective parameters, characterizing the chain of cascades as a whole.

2. The effective parameters can be calculated using the formulas (12)-(15), using experimental results.

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