Methods of Reducing Temperature Losses on the Intermediate Substrates of Multistage TE Modules

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Abstract

Temperature distribution on intermediate substrates of multistage thermoelectric (TE) modules is analyzed. It is shown that, depending on various thermal conditions of TE pellets operation, the temperature in the center of the substrate may significantly exceed the temperature on its edges, especially if the substrate material has a relatively low value of thermal conductivity (for example, ceramics based on Al_2O_3). To reduce heat losses it is suggested that TE modules with pellets cross-section widely varying from stage to stage should be applied. It results in decreasing intermediate substrates sizes and thus intensifying the heat flux density across them. This heat flux density growth makes the TE module more efficient as the pellets on the edge of the substrates are better involved in cooling. Some practical approaches of realizing this idea with the pellets connected in series and in parallel are studied.

Introduction

Consider methods of reducing temperature losses on the intermediate substrates of multistage TE modules. For narration convenience we suggest beginning cascade numeration from the coldest stage, which is the first one. The heat rejected by it is the heat load of the second stage and so forth.

The ratio between pellets numbers of sequential stages (the so called cascading coefficient) being restricted is the main obstacle interfering with extremely low temperature cooling by a TE module. Those restrictions are resulted from the temperature distribution over the substrate surfaces between the module stages. Due to that, the temperature at the substrate centre directly under the previous stage turns out higher than that at the substrate edge. To avoid this unwelcome phenomenon it is efficient to apply the materials of higher thermal conductivity such as BeO and AlN for the substrates, but it makes a TE module quite more expensive. Besides, in powerful TE modules (with large substrate surfaces) even at moderate cascading coefficients the distance between the boundary pellets of the *i*-th stage and those of the (*i*-1)-th stage may significantly exceed the substrate thickness, which makes the thermal resistance between these pellets higher as compared to the thermal resistance between central pellets of the same stages. If thermal conductivity of ceramics, which is commonly the substrate material, is high, temperature losses might be inconsiderable. That is all well-known at the qualitative analysis level, but quantitative estimates have not been carried out so far. The approach developed in [11] allows doing that. Therefore let us quantify the problem of reducing temperature losses in a TE module.

Suppose that the electrical connection between the cascades can be of any type. The optimal sequence of the temperatures [2] of the cascades certainly does not depend on their electrical commutation. That is why we consider it determined and consistent with the properties of the applied TE materials. Let us define the geometrical factor of a pellet as the ratio *s/L*, where *L* is the pellet height and *s* is its cross-section. Note that if the geometrical factor is the same at all the stages, there is no essential difference between both the feed types. The series connection provides approximately one value of the optimal electric current for all the cascades, the parallel connection allows grouping the cascades of one voltage supply. Involuntary deviation from the optimal number of pellets per stage, induced by geometry and design reasons, is approximately the same for the two feeding types. But the series connection is less sophisticated, which explains its preference in the large majority of applications.

Methods of Reducing Temperature Losses on the Substrates

It is evident from the qualitative point of view that there is minimum of thermal losses in case the difference between the *i*-th and the (*i*-1)-th substrate dimensions is less than the substrate double thickness. The surface of the next stage substrate as compared to the previous one can only be decreased if the heat flux density of the *i*-th stage cooling capacity grows. This growth may result not in additional temperature losses on the substrate as it seems on the face of it, but in their reduction, for the edging pellets of the *i*-th stage work more efficiently.

The pellet cooling capacity of the *i*-th stage may grow due to either diminishing pellets height, or increasing the pellets filling coefficient $K_f = \frac{ns}{S}$, where *n* is the stage pellets number, *S* is the stage cold substrate area. If the cascades are connected in series, reducing pellets cross-section while the geometrical factor remains constant, does not require any changes in the cascade-to-cascade agreement to electric current. The smaller cross-section of the pellets, the higher cooling capacity density of the *i*-th stage. Besides, decrease of the pellets cross-section may be accompanied by shortening the distances between the pellets, which can raise K_f as well as intense heat fluxes density. The optimal electric current for the multistage TE module *i*-th cascade in the mode of the maximum coefficient of performance ε is equal to [2]:

$$I_{\varepsilon i} = \frac{\alpha_i \Delta T_i}{R_i (M_i - 1)}, \qquad (1)$$

where α is the TE material Seebeck coefficient, ΔT is the stage temperature difference, *R* is the pellet resistance, $R = \rho \frac{L}{s}$, ρ is TE material electric resistivity, and $M = \sqrt{1 + ZT_{av}}$ (*Z* is TE material Figure-of-Merit and T_{av} is the stage average temperature), the index *i* indicates the stage number. If with the stage number *i* rising, we take TE materials of smaller α and, accordingly, bigger electric conductivity, the relative value $\alpha\sigma$ grows and for keeping I_ε constant the pellet has to be taken higher, which is more convenient from the point of view of design arrangement. If the value $\alpha\sigma$ grows, the cooling capacity value Q_0 of a pellet slightly degrades

$$Q_{\varepsilon 0i} = I_i^2 R_i M_i \varepsilon_i \qquad (2)$$

However it must be compensated by the growth of the filling coefficient.

The described above is illustrated by the example of a two-stage TE module. Without taking into account any temperature losses on the intermediate substrate this module can yield ΔT_{max} = 85 K if cooling down from 300 K at the heat load 0.6 Вт. The materials parameters used in the calculations are given in Table 1. The distance between the pellets is 0.8 mm, the intermediate substrate dimensions are 21.6x21.6 mm^2, and those of the first stage cold substrate are 10.8x10.8 mm^2 (the same surface was taken as the thermal contact area between the first and the second stage). The first stage is mounted on the second one so that their centres of symmetry coincide. The substrate thickness is 1 mm. The substrate material is the ceramics Al_2O_3, thermal conductivity is 28 W/mK. The filling coefficient of the second stage is 0.308.

Table 1

The two-stage TE module parameters at 300K as well as pellets geometry and number per stage

Stage Number	α , μV/K	σ, Ohm^{-1}cm^{-1}	κ, W/mK	Pellet Dimensions, mm^3	Pellets Number
1	240	690	1.45	1x1x1.5	36
2	210	910	1.5	1x1x2.1	144

The temperature distribution on the intermediate substrate surface along the line parallel to one of the substrate sides and crossing the centre of symmetry, calculated with the help of [1], is given in Fig. 1.

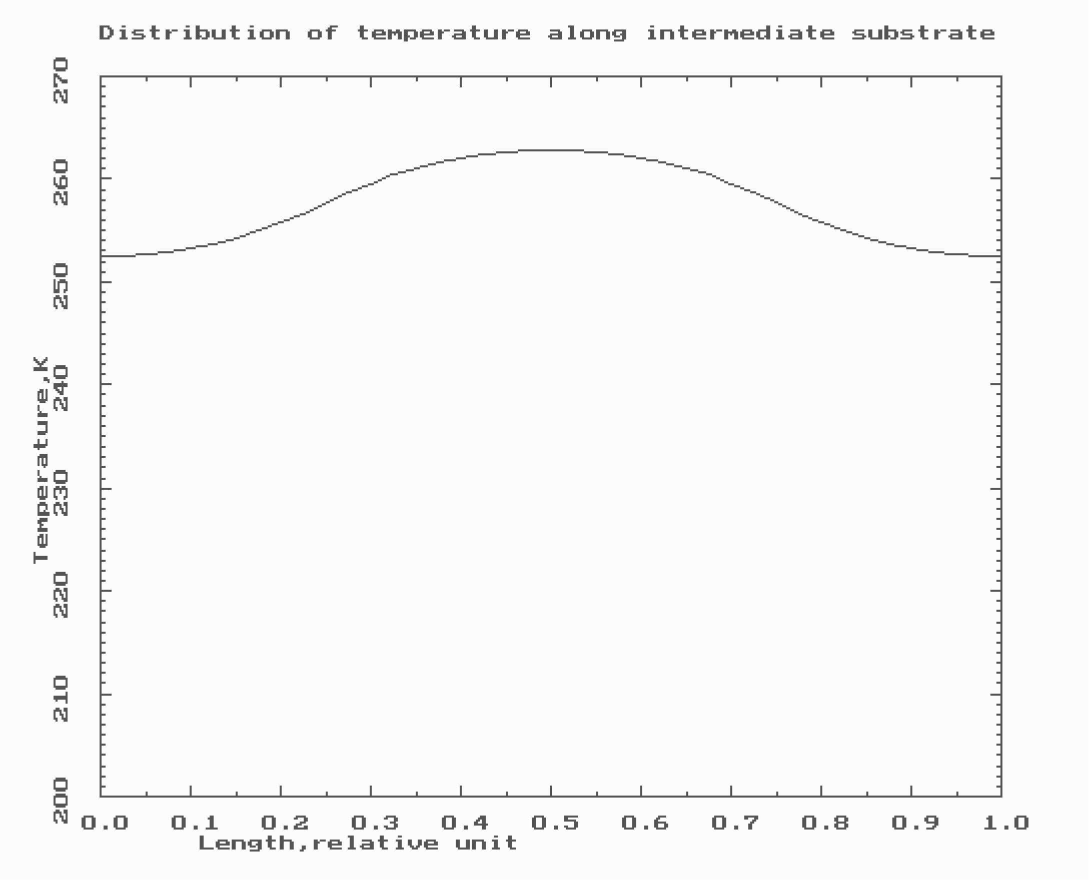

Figure 1: Central section of the 2D-temperature field on the intermediate substrate of the two-stage TE module

From the figure it can be seen that the temperature at the centre of the substrate is 10 K higher than the temperature at its edges. The difference of the temperatures averaged over the whole substrate and the first stage area is lower and equals 6.3 K. It should be regarded as the criterion describing temperature losses on the substrate. These losses will not allow achieving the calculated temperature difference (85K). If the substrate were made of AlN, whose thermal conductivity is 150 W/mK, the thermal losses on it would be much less and equal as little as 1 K.

Now let us try to take the pellets in the second stage 0.7 x 0.7 mm^2 wide and 1 mm high. That is, the deviation from the original value *s/L* is less than 3%. Let us reduce the distance between the pellets to 0.4 mm. The substrate area becomes smaller: 13.2 x 13.2 mm, and the filling coefficient is now 0.406. The corresponding temperature distribution on the intermediate substrate surface along the same direction, as it was in Fig. 1, is given in Fig. 2.

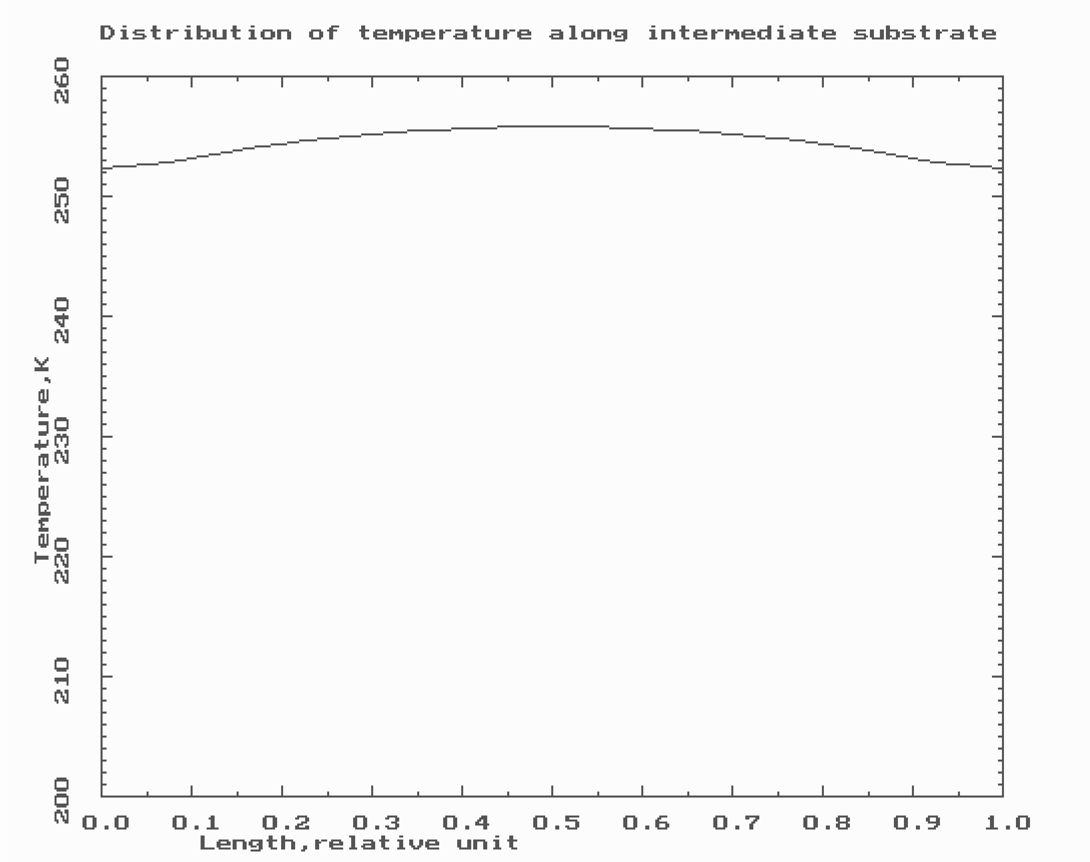

Figure 2: The temperature distribution on the intermediate substrate surface along the same direction as it was in Fig. 1 but for the lesser cross-section and filling coefficient of the pellets in the second stage

We see a good temperature smoothing over the substrate. The average temperature difference fell to 1.2 K. The effect is the same as if AlN had been taken for the substrate material instead of Al_2O_3.

Thus, it is clear that in case of the series feeding the usage of narrower pellets arranged with a higher filling coefficient make thermal losses on the substrate much lower.

The same phenomenon may be observed for the parallel feeding as well.

In this case the optimal voltage on the pellet does not depend on its geometry:

$$U_{\varepsilon i}=\frac{\alpha_i \Delta T_i M_i}{M_i-1} \tag{3}$$

The pellet optimal cooling capacity $q_{0\varepsilon i}$ is now in inverse proportion to the pellet electrical resistance:

$$q_{0\varepsilon i}=\frac{U_{\varepsilon i}^2 \varepsilon_i}{R_i M_i}, \tag{4}$$

where ε_i is the coefficient of performance. So, the application of TE material with higher electrical conductivity for the lower stages improves each pellet cooling capacity.

The voltage *Ui* of the *i*-th stage determines the stage pellets number. For instance, in the first stage after choosing the pellet geometry the necessary cooling capacity is provided by the pellets number n_1, and $U_1=U_{\varepsilon 1}n_1$. In case of the parallel communication of the cascades the second stage voltage equals that of the second one, and its pellets number is given by:

$$n_2=\frac{U_{\varepsilon 1}n_1}{U_{\varepsilon 2}}. \tag{5}$$

The pellets numbers of the next stages are described by similar expressions. Using for the first stage the same configuration as it was for the series feed and applying for the second stage the

TE material with properties of Table 1 (stage 2) we obtain that in the second stage there should be approximately 36 pellets. The necessary cooling capacity of the second stage is 3.3 W, therefore with the help of Eq. (4) we obtain the ratio *s/L*=2.5 mm. Knowing it and specifying the pellet cross-section, we can find the pellet height. If the pellet cross-section is 1.4 x 1.4 mm^2 and the distance between the pellets is 0.8 mm, the substrate size remains the same as in the case of the series feed of the stages (13.2 x 13.2 mm^2), the filling coefficient is now 0.52. Then the pellet height is equal to 0.8 mm. All this provides the two-dimensional temperature filed on the intermediate cascade similar to the one demonstrated in Fig. 2.

So, assuming that pellets cross-section can vary from cascade to cascade, it is possible to reduce thermal losses on the ceramic substrates and minimize the module dimensions.

There is no key difference between the series and parallel feed of the TE module cascades, but the advantage of the series connection is electric current agreement of stages whereas the parallel connection has to put up with the electric current increase and therefore geometrical factor modification, which sometimes might be quite inconvenient.

Conclusion

The paper proves that a usage of combined commutation of cascades in multistage TE modules, as well as geometry and TE material per cascade optimization allow a considerable gain in cooling efficiency as a result of reduction of two-dimensional temperature losses on intermediate substrates.

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1. Drabkin I.A., Yershova L.B., Kondratiev D.A., Gromov G.G. The Effect of the Substrates Two-Dimensional Temperature Distribution on the TEC Performance. Proc. of VIII European Workshop on Thermoelectrics, Poland, Kraków, 2004.
2. Vayner A.L. Cascade Thermoelectric Coolers (Moscow, 1976), P. 176