UDC 658.51.011.56

A.M. SINOTIN, Doct. of Tech. Sc., O.M. TSYMBAL, Doct. of Tech. Sc.,
T.A. KOLESNIKOVA, Cand. of Tech. Sc., S.V. SOTNIK, Cand. of Tech. Sc.

ALGORITHM OF MULTI-BOARD RADIO-ELECTRONIC DEVICES SYNTHESIS ON MAXIMAL ACCEPTED OVERHEAT

During the design of Radio-Electronic Devices (RED), the thermal modes get more and more attention of engineering personnel. It's explained by a number of reasons: the essential part of different energy forms (nearly 90%) is transformed to the heat, what increases the temperature of the whole radio-electronic device. And finally, the reliability of device's parts drops with temperature rise.

The temperature increase in RED degrades the isolation properties of particular materials, changes the density and movement of electric current carriers in semiconductors, increases the velocity of material's ageing, decreases the saturation inductance for cores and etc. All theses make an effect to the accuracy characteristics of the whole device and even can result in its destruction.

The ability to compute the temperature of particular parts of device during the design process provides more accurate calculations of electric and magnetic circuits and opens the possibility of economic foundation of any variant for designed device construction [1].

Therefore, to create the reliable small-sized construction of RED, the thermal-physical procedure must be supplied at every stage of construction design.

Goal of research – is to establish the value of RED's volume effect to the temperature mode of proposed construction.

Task setting

The sources in field of thermal-physic design for REDs with given thermal mode are mostly presented by articles [1, 2]. Their main efforts are directed to the selection and optimal application of air-cooling systems. The monographs on general RED design consider the testing computations for thermal fields only. The thermal-physic design is provided only by multiple calculations with different parameters values, so it uses the method of trial and error. The proposed article gives the results of researches for the effect of heated zone form to the maximal overheat of device.

Basic part

The multi-board constructions always have got the thermal connections between the elements and boards, because of assembly density coefficient $l_{max}/\Delta > 1$. It makes possible to consider the heated zone as quasi-homogeneous body with effective heat conduction λ_x, λ_y along board axis and λ_z in board-normal direction [1].

The numeric values of effective thermal conductivity for REDs with air extender are considered in [1] for functions of clearance Δ between boards for middle assembly density ($\eta_м > 1$) and for non-thermo-conductive boards. For non-thermo-conductive boards with big assembly density:

$$\lambda_0 = \lambda_x \approx \lambda_y \approx \lambda_z = 0.2 \text{ W / m} \cdot \text{degree}. \quad (1)$$

For case of thermal-conductive boards (thermal drains) the effective thermal conductivity is defined along the thermal drains by dependence

$$\lambda_i = \lambda_{oi}\left(1 + \frac{\lambda_H}{\lambda_{oi}} \cdot \frac{\delta_M}{\Delta + \delta_M}\right); \text{ i= x, y, z,} \quad (2)$$

where λ_{0i} – effective thermal conductivity for non-thermal-conductive boards, W/m ·degree;

$\lambda_н$ – thermal conductivity of solid metal boards (thermal drains), W/m ·degree;
$\delta_м$ – width of metallic boards (thermal drains), m;
Δ – distance between boards, m.

The connection between the thermal field of anisotropic heated zone of RED in parallelepiped form, the thermo-physical coefficients (λ, c, γ), symmetrically allocated heat sources and drains, as to [1] is expressed by integral equation

$$\frac{\int_0^{\ell_x}\int_0^{\ell_y}\int_0^{\ell_z}\int_0^{\tau}\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty}\frac{w(x',y',z',\tau)-Q(x',y',z',\tau)}{c\gamma}u_{nx''}\times u_{my'}u_{kz'}u_{nx}u_{my}u_{kz}}{\int_0^{\ell_x}\int_0^{\ell_y}\int_0^{\ell_z}u_{nx'}{}^2u_{my'}{}^2u_{kz'}{}^2dx'dy'dz'}\times \tag{3}$$
$$\times\frac{e^{-\frac{a_n^2}{c\gamma}(\tau-t)-\frac{q_v}{c\gamma}t}}{dx'dy'dz'dt}=\vartheta(x,y,z,\tau)$$

The derivation of synthesis algorithms for general temperature change law $\vartheta(x, y, z, \tau)$ on base of expression (3) has essential mathematic complexity, because the methods of incorrect multi-dimensional problem had found their solutions last year’s only.

That’s why we’ll narrow by case when the required thermal mode is set by maximal temperature for the established mode $\vartheta_0\,(\tau\to\infty)$.

The solution of equation (3) is got for symmetric laws of energy sources and drains distribution.

Taking in account these proposals, let’s narrow with first member of general solution at $\tau\to\infty$ and get the dependence of maximal temperature and other all parameters of thermal process.

$$\frac{P}{\lambda_{max}}\cdot\frac{\ell_{min}{}^2}{v}\zeta^2F_w\times\frac{A}{(\mu_x\xi_x)^2+(\mu_y\xi_y)^2+(\mu_z\xi_z)^2+\dfrac{q_v\ell^2_{min}\,\zeta^2}{\lambda_{max}}}=V_0\,; \tag{4}$$

$$A=\left\{\begin{matrix}0.82A_xA_yA_{z,}\ \xi_x\approx\xi_y\approx\xi_z=1\\ A_xA_y\qquad \xi_x\approx\xi_y;\xi_z\to 0\\ A_x\qquad \xi_y\approx\xi_z\to 0\end{matrix}\right\}. \tag{5}$$

The ability to narrow the sum by first member of set (6) under conditions (5) is seen in Table 1.

$$\vartheta=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty}\frac{W_0}{\lambda_{max}}\ell^2_{min}\zeta^2F_{n,m,k}(W)\times\frac{A_{nx}A_{my}A_{kz}}{\mu^2_{nx}\xi^2_x+\mu^2_{my}\xi^2_y+\mu^2_{kz}\xi^2_z+\dfrac{q_v\ell^2_{min}\zeta^2}{\lambda_{max}}}\times \tag{6}$$
$$U_{nx}U_{ny}U_{nz}T_{n,m,k};$$

Let's signify in (4) the minimal linear size of heated zone in form of parallelepiped 2 ℓ_{min} via the fixed volume V (m^3) and the relational dimensions of sides.

Table 1

Type of prism	*Sum of series*	First term	Accuracy %	Correction
Cube	0.223	0.273	22.5	0.82
Square bar	0.297	0.332	11.8	0.90
Square plane	0.500	0.510	2.0	0.98

$$V = 8\ell_x \ell_y \ell_z = 8\ell^3_{min} \frac{1}{\xi_{x0} \cdot \xi_{y0} \cdot \xi_{z0}}; \quad (7)$$

$$\ell_{min} = 0.5\sqrt[3]{V}\sqrt[3]{\xi_{x0} \cdot \xi_{y0} \cdot \xi_{z0}}; \quad (8)$$

$$\xi_{i0} = \frac{\ell_{min}}{\ell_i}, \qquad i = x, y, z \quad (9)$$

After the substitution of (8) and values λ to (4) and parameters grouping we can come to mathematic expression of RED synthesis algorithm for given maximal temperature in a view of connective equation between synthesis parameters F_j with no volume energy drains ($q_v = 0$).

$$F_0 \cdot F_Ф \cdot F_\lambda \cdot F_{a\lambda} \cdot F_{ak} \cdot F_w \le 1; \quad (10)$$

here F_0 – initial parameter,

$$F_0 = \frac{P_0}{\vartheta_0} \cdot \frac{1}{4\lambda \cdot \sqrt[3]{V}} \cdot \frac{0{,}82 A_0^3}{3\mu_0^2}; \quad (11)$$

$$Bi_0 = \frac{K_0}{\lambda_0} \cdot \frac{1}{2} \cdot \sqrt[3]{V}, \quad (12)$$

here P_o – total power of heat sources, W; ϑ_o – maximal possible overheat of device, degree; λ_o – the effective thermal conductivity with no drains at gas extender, W/m• degree;V_0 – the volume og heated zone, m^3; A_o, μ_o – the amplitude and eigenvalues of characteristic equation for B_{I_o}; K_o – the middle surface coefficient of heat transfer W/m^2 • degree.

Initial parameter F_o describes the heat mode of RED construction:

– the heated zone has form of cube

$$\left(\xi_{X_o} = \xi_{Y_o} = \xi_{Z_o} = 1\right) \quad (13)$$

here $\xi_{I_O} = 2l_{mii} / 2l_i, i = X, Y, Z;$

- the anisotropy of heat transfer in volume and of heat exchange is absent $\left(\lambda_X = \lambda_Y = \lambda_Z = \lambda_o; K_X = K_Y = K_Z = K_o\right)$

- the conductive thermal drains are absent $(\lambda_{max} = \lambda_o)$;

- the heat sources power is evenly distributed.

The parameter of parallelepiped form is included by relational length of sides

$$F_ф = 3\frac{A_1}{A_0^3}\mu_0^2 \frac{\sqrt[3]{\xi_{x0}^2 \cdot \xi_{y0}^2 \cdot \xi_{z0}^2}}{(\mu_{x1} \cdot \xi_{x0})^2 + (\mu_{y1} \cdot \xi_{y0})^2 + (\mu_{z1} \cdot \xi_{z0})^2}; \quad (14)$$

$$B_{i1} = B_{i0} \frac{\sqrt[3]{\xi_{x0} \cdot \xi_{y0} \cdot \xi_{z0}}}{\xi_{i0}}; i = x, y, z; \quad (15)$$

$$A_1 = A_{x1}^* \cdot A_{y1}^* \cdot A_{z1}^*; \quad A_{i1}^* = A_{i1} - (A_{i1} - 1)(1 - \xi_{i0}); i = x, y, z, \quad (16)$$

with $\xi_{и0}$ – relational lengths of parallelepiped sides (9);

A_{i1}; $\mu_{и1}$; A_0; μ_0 – the values of amplitudes and of eigenvalues for criterions Bi_0 and Bi_1 (Table 2);

Figure 1 shows the dependence of parameter $F_o \cdot \vartheta_o / P_o \cdot 10^2$ from the volume of device's heated zone and of heat transfer coefficient K_o, which describes the system of surface cooling for devices the effective heat transfer $\lambda_o = 0{,}2$ W/m·degree [1]. Its follows from charts, that the initial parameter F_o can be minimized by reduction of relationship P_0 / ϑ_0, by enlargement of heated zone volume V and of surface heat exchange intensity K_o.

Let's consider every factor by parts. The reduction of relationship P_0/ϑ_0 sets some demands to development of device's electric scheme. F_λ is a parameter of effective heat transfer for heated zone.

$$F_\lambda = \frac{1}{1 + \frac{\lambda_M}{\lambda_0} \cdot \frac{\delta_M}{\Delta + \delta_M}} \cdot \frac{A_2}{A_1} \times \cdot \frac{(\mu_{x1} \cdot \xi_{x0})^2 + (\mu_{y1} \cdot \xi_{y0})^2 + (\mu_{z1} \cdot \xi_{z0})^2}{(\mu_{x2} \cdot \xi_{x0})^2 + (\mu_{y2} \cdot \xi_{y0})^2 + (\mu_{z2} \cdot \xi_{z0})^2}; \quad (17)$$

$$B_{i2} = B_{i0} \frac{\sqrt[3]{\xi_{x0} \cdot \xi_{y0} \cdot \xi_{z0}}}{\xi_{i0}} \cdot \frac{\lambda_0}{\lambda_{max}}; \quad i = x, y, z; \quad (18)$$

$$\frac{\lambda_0}{\lambda_{max}} = \frac{1}{1 + \frac{\lambda_M}{\lambda_0} \cdot \frac{\delta_M}{\Delta + \delta_M}}; \quad (19)$$

$$A_2 = A_{x2}^* \cdot A_{y2}^* \cdot A_{z2}^*; A_{i2}^* = A_{i2} - (A_{i2} - 1)(1 - \xi_{i0}); \quad i = x, y, z, \quad (20)$$

with A_{i2}, μ_{i2} – values of amplitudes and eugenvalues for Bi_{i2} (Table. 2).

For the implementation of scheme solutions it is rational to select the electronic components with minimal power consumption and the materials with high thermal resistance. If it's need to use some elements with small possible overheat temperature ϑ_o, the rational way is in selection of them in separated group to simplify the supplement of given thermal mode of general device construction. Such method is very important for selection of electronic components of electric scheme, because the given electric scheme makes designer without possibility to manipulate the factors of power dissipation and of thermal resistance of scheme's elements.

The dependence analyses (see Figure 1) shows, that for one-block cubic device constructions with size $\sqrt[3]{V} \geq 0{,}5$ m, the minimization of initial parameter F by heated zone enlargement (with elements allocation density) and by transition to more intensive surface cooling system $K_0 = \infty$ becomes practically impossible.

Table 2

B_i	A_i	M_i
0,00	1000	0,0000
0,01	1,1020	0,0998
0,10	1,0159	0,3111
0,50	1,0701	0.6533
0,60	1,0813	0,7051
0,70	1,0918	0,7506
0,80	1,1016	0,7310
0,90	1.1107	0,8274
1,00	1,1192	0,8603
2,00	1,1784	1,0769
3.00	1.2102	1.1925
4.00	1,2287	1.2646
5,00	1,2403	1.2138
10,00	1,2612	1.4289
2.00	1,2699	1,4961
30.00	1,2717	1,5202
40.00	1.2723	1.5325
50,00	1.2727	1.5400
100	1,2731	1.5552

On the contrary, for constructions of size $\sqrt[3]{V} \le 0{,}5$ m, the volume and K_o increase lead to triple reduction of F_o at $\sqrt[3]{V} = 0{,}1$ m and for 50% at $\sqrt[3]{V} = 0{,}3$ m by changing K_o from 4 W/m^2*degree to ∞. Practically, even at $K_o \ge 100$ W/m^2•degree there is an ultimate case, therefore for devices with gas extent (with small thermal conductivity $\lambda_o = 0{,}2$ W/m*degree) it is not rational to apply the liquid and other more effective systems of surface cooling (the values of coefficients can be seen from Table 3).

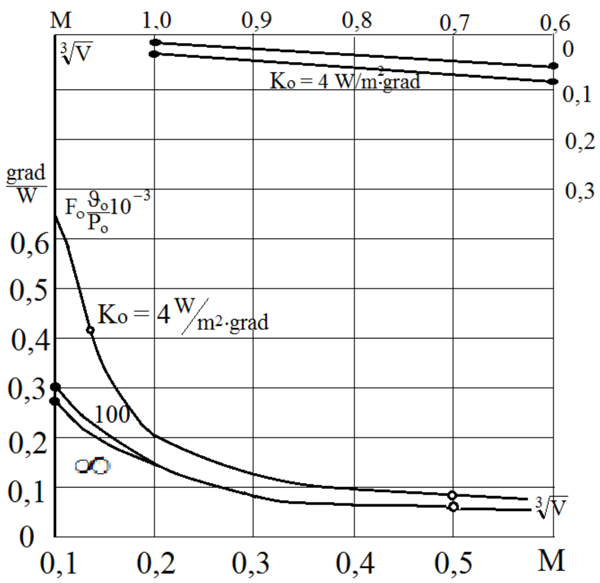

Figure 1. Dependence of initial parameter F_0 of heated zone volume ($\sqrt[3]{V}$)
and of surface heat exchange intensity K_o for λ = 0,2 W/m $\cdot$degree

Table 3

№	*Type of cooling system*	α^* W/m · degree
1	Common action of natural convection and radiation with blackness level from 0 to 1 for air	5-10
2	Forced convection for air (gas) by blowing of surface with different speed	10-100
3	Natural convection by oil or liquid of similar density	200-300
4	Natural convection by water	20-600
5	Forced convection by oil	300-1000
6	Boil on cooling surface	1000-3000

The ultimate minimization of F_o can be achieved by application of forced convective air cooling (α =10-100 W/m * degree) [3].

Heat transfer coefficient

$$K_o = \frac{K^1 S_k / S}{1 + K^1 S_k / \alpha S}\ , \qquad (21)$$

with K_o –heat exchange coefficient for gas interlayer from heated zone to cover, W/m^2* degree; α - heat exchange coefficient between cover surface and surrounding zone, W/m^2*degree; S_K , S , – squares of cover and heated zone surfaces, m^2.

The analysis of expression (4) for heat transfer coefficient K_0 and Table1 for values of thermal exchange for different types of cooling systems [3] gives possibility to set two ways to enhance K_0 for minimization of parameter F_0 and construction synthesis with given thermal mode on maximal overheat. First way is clearly constructional for small values of K_o and is suitable for radio-electronic devices, functioning in natural air-cooling conditions.

The computations, provided for a great number of device constructions [2] show the equality of conductivities between the heated zone and cover, also surrounding space:

$$K^1 \cdot S \approx \alpha \cdot S_K \qquad (22)$$

After the substitution of (5) to (4) there is $K_O = \alpha \cdot S_K$, so the application of device cover brings down the efficiency of surface cooling nearly twicely.

Superposition of device cover with heated zone gives $(S_K = S)$, $K^1 \to \infty$ and $K_o = K$.

Therefore, in a constructive way, the superposition of device cover with heated zone gains K_o twicely (рис. 2)

To do this, there must be supplied good thermal contact between heated zone and cover, for instance by application of high-thermal-conductive pastes in joints between boards (chassis), cover edges etc. The considered method is most effective when tightness of device (dust protection) must be kept. Also other constructive way is possible: to reduce the cover effect of thermal drains intensity by defection of tightness and by direct contact of heated zone cooling air to perforated holes (jalousies).

Therefore, the expression for K_o in a first approach will be of next view:

$$K_0 = K^{\bullet}{}_0 (1 + S_{per} / S_k), \qquad (23)$$

where S_{per} – square of perforated holes, m^2; K_o is defined by expression (6) for $S_{per} = 0$. Relation S_{per} / S_K is a perforation coefficient. More exactly perforation is taken in account by [3]. Really, already for $S_{per.}/S_K = 0,5 - 0,6$, value of K_O is close to K_o^*, so the ultimate minimization effect F_O is achieved.

The considered constructive methods give no possibility for essential change of heat transfer coefficient K_0 .

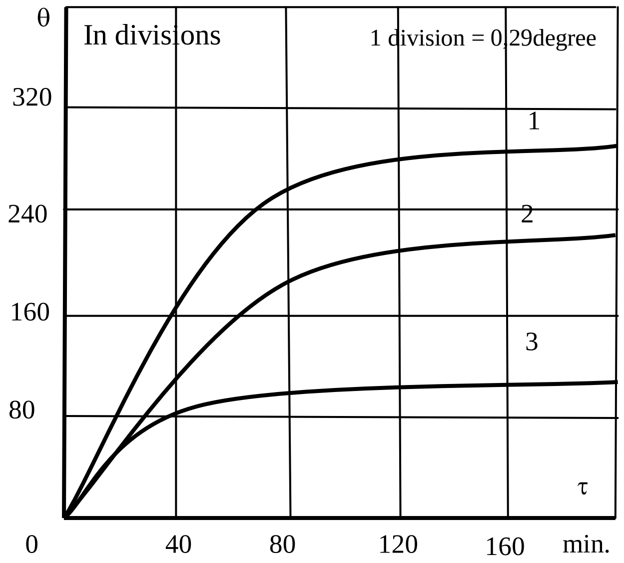

Figure 2. Temperature values for central point of heated zone:
1 – with no thermal drains; 2 – with thermal drains; 3 – with thermal drains to device cover

For the essential change of heat exchange at heated zone surface there is need the transition from natural to forced surface cooling by air blowing, so the additional changes are required. So, as to (2) there is need to enhance the heat exchange intensity between heated zone and cover (K^1), or between cover and surrounding space (α), or to superpose cover to heated zone $(K^1 \to \infty)$. Otherwise, the rise of K_O will be small, while essential rise of α. Therefore, the second way of F_0 minimization by increase of K_0 means the transition to new cooling system with superposition of cover and heated zone, especially for construction with high density assembly.

The rise of heated zone volume by reduction of element's allocation density is opposite to request of constriction size minimization and can be applied only if no hard limitation for construction sizes in project documents exists.

Practically, the 8-scale change of volume (for range $\sqrt[3]{V}$ < 0,5 m) leads to triple reduction of F_0 then K_0 = 4 W/m · degree and to twice reduction then $K_0 = \infty$ (see picture). Such change of volume can be supplied by transition from high density assembly $(\eta_м \geq 1)$ to low $(\eta_м \approx 1)$.

Conclusion and perspective:

1. The effective minimization of initial parameter can be provided for device constructions with linear size less then 0,5 m, by transition to low density or surface cooling efficiency enhancing. For construction with linear size greater 0,5 m the initial parameter minimization is practically impossible.

2. It's obtained, that transition to square bar construction supplies the most effective minimization of form parameter. The level of minimization rises with efficiency of device's cooling system.

3. The level of thermal conductivity parameter minimization depends of cooling system and linear size of device. For linear size more 0,5 meter, or for intensive surface cooling there is an extreme minimization of thermal conductivity parameter. It's obtained, that the rise of effective thermal conductivity more then 2-4 W/m · degree doesn't supplies the next minimization. Correspondently, the rise of thermal conductivity of extenders (compounds) more the mentioned values isn't rational.

4. The minimization of thermal conductivity anisotropy parameter makes demands on such allocation of boards, that the minimal sizes of heated zone of device are the same as action of direction for maximal thermal conductivity. For the optimal form of square bar of flat thermal drains it defines the demand on square boards allocation perpendicular to big axis of bar, that leads to extreme minimization of thermal conductivity anisotropy parameter. The violation of such condition sharply declines the efficiency of conductive thermal drains application.

5. The concentration of heat-dissipating elements to the center of heated zone promotes the rise of power parameter and therefore has negative effect to thermal mode of elements in comparison to regular allocation of power sources.

6. The minimization of power parameter is possible by concentration (allocation) of heat-radiating elements on device's heated zone periphery. The level of minimization is determined by intensity of device's surface cooling, by value of effective thermal conductivity of heated zone and by board sizes. For the devices with linear size less then 0,5 m and small efficiency of surface cooling or with more effective thermal conductivity, the law of heat-radiating elements concentration practically has no effect to power parameter in comparison to flat distribution. There is an effect of transition of maximal temperature from central zone to periphery (Figure 2).

7. In the device with plane thermal drains for the conditions of natural convection the irregularity of power distribution really has no effect to maximal overheat.

8. The optimal form and allocation of boards with elements in heated zone volume are defined by minimization conditions for thermal conductivity anisotropy parameter and the optimal allocation of elements on boards is derived from minimization of power parameter.

9. It's shown, that if minimization of all the synthetic parameters for the given limitations doesn't supply the inequality (10), it's need to cross from surface cooling systems to more constructively complex volume cooling systems. In that case, the synthesis of device leads to optimal selection of cooling system parameters.

References: 1. *Semenets, V.V., Sinotin, A.M., Kolesnilova, T.A.* Regular thermal mode accuracy research on thermal fields calculation for heated zones of radio-electronics devices. – 2016. – 172 p. 2. *Semenets, V.V., Sinotin, A.M*. Regular thermal mode accuracy research on thermal fields calculation for heated zones of radio-electronics devices // Sistemi obrobki informacii. – 2016. – №3. – P. 100-102. 3**.** *Dulnev, G.N., Tarnovsky, N.N.* Thermal modes of Radio-Electronics Devices. – 1971. – 248 p.

Харьковский национальный
университет радиоэлектроники

Поступила в редколлегию 15.08.2017