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**RESULTS OF THEORETICAL RESEARCH ON COOLING SYSTEM  
FOR RADIO ELECTRONIC EQUIPMENT ELEMENTS  
WORKING IN THE INTERMITTENT HEAT  
RELEASE MODE**

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*The paper deals with cooling system for radio electronic equipment elements working in the intermittent heat release mode based on melting working agents with the additional heat removal via a thermopile. The basic design ratios for its theoretical study are given. Dependences of REE element stable operation time, as well as its temperature characteristics with provision of its thermal conditions by the system in question are represented.*

**Key words:** cooling system, REE element, heat exchange, melting working agent, melting, solidification, thermopile, simulation.

## **Introduction**

In the design of radio electronic equipment (REE) intended for work in a wide range of thermal loads, one has to take into account the impact of temperature on its characteristics and parameters. If the latter go beyond the limits permissible for its normal operation, recourse is made to some or other cooling and temperature stabilization methods.

At the present time, in the practice of REE design, various methods are used for provision of its thermal conditions, among which special mention should go to air, liquid, conductive, evaporative, thermoelectric, and some special methods [1 – 3]. Each of the above methods has its strong and weak points. In particular, REE cooling on the basis of air and conductive methods is inefficient because of the low intensity of heat removal and temperature accuracy. Liquid and evaporative thermal stabilization system is difficult to make and requires bulky equipment of complicated design. Moreover, in this case a source of electric energy is needed for power supply to cooling systems.

A promising method for cooling REE working in the intermittent heat release mode is based on the use of melting working agents with a stable melting temperature [4]. Structurally, devices that implement this method have the form of a container filled with a melting working agent. A REE element is brought into direct contact with this container and can be arranged both inside the container and on its surface [5]. During operation, the basic part of heat dissipated by equipment element or unit is absorbed due to latent heat of agent melting. On termination of equipment operation, the agent is cooled down and solidified as a result of heat exchange with the environment.

The main disadvantage of such systems restricting their application for cooling REE with high heat flux densities is a need to maintain working agent in the state of phase transition during the entire operation period of electronic device. Since the element, while in operation, releases considerable powers, in many cases the heat storage capacity of working agent proves to be insufficient to provide for the required temperature mode during the entire operation period (working

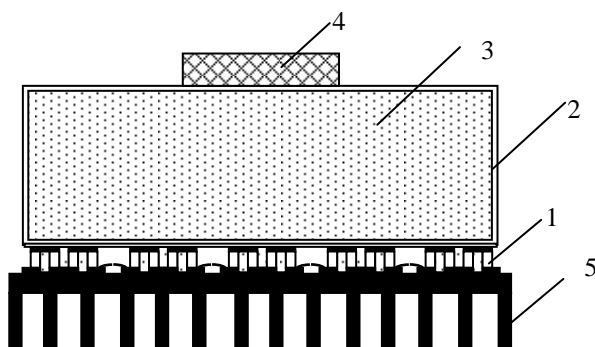
agent will be clear-melted by the end of the element operation cycle).

In this context, on cooling of high-power radio electronic devices with the use of melting working agents it is worthwhile to use some additional cooling system for removal of excess heat from the working agent. As regards the energy and mass-dimensional parameters, good use can be made of a thermopile as such additional cooling system. A similar system was considered in [6], where its different embodiments are described, characterized in different ways of orientation of a container with melting working agent and a thermopile, as well as in different operation modes.

The purpose of this paper is development of a mathematical model and theoretical studies of the herein described system of heat removal from REE elements working in the intermittent heat release mode which is based on a joint use of working agents melting in given temperature range and thermoelectric cooling method.

### **Design of cooling system for radio electronic equipment elements working in the intermittent heat release mode**

Fig. 1 represents structural schematic of system under consideration, and Fig. 2 – its appearance. Here, thermopile 1 is brought into good thermal contact with the end surface of a thin-walled metal container 2 filled with working agent 3, on the other surface of which a radio electronic equipment element 4 is mounted. The thermopile works in the intervals of heat release element operation.



*Fig. 1. Structural schematic of a system for cooling radio electronic equipment elements working in the intermittent heat release mode.*



*Fig. 2. Appearance of a system for cooling radio electronic equipment elements working in the intermittent heat release mode.*

The operating principle of device is as follows. Heat coming from REE element 4 is passed to metal container 2 and through contact surface to working agent 3. Then there is a simultaneous warm up of working agent 3 to melting temperature, and melting process takes place accompanied by absorption of heat released by REE. On termination of operating cycle of REE element 4, the working agent 3 is cooled down and solidified due to heat removal by thermopile 1 working in cooling mode. Solidification time of working agent 3 in this case is attained by increasing the intensity of heat removal.

### **A mathematical model of cooling system for REE elements working in the intermittent heat release mode**

Mathematical simulation of cooling system considered includes investigation of

thermophysical processes upon melting and solidification of working agent, as well as calculation of an appropriate thermopile.

Simulation of processes related to a change in the aggregate state of working agent was done by solving Stephan's problem with the use of Leybenzon's method [7]. The principle of the approximate solution method lies in the selection of such functions of the liquid and solid phase temperature variation that would meet the required initial and boundary conditions. The thus selected functions are substituted into phase matching condition at phase interface, and the resulting differential equation is solved for phase interface coordinate. For the case under consideration the temperature profiles in the solid and liquid phase are represented as a polynomial dependence in conformity with recommendations [4].

As a result, the following equation systems were obtained for research on the processes of melting and solidification of working agent with and without convective fluxes in the liquid substance phase:

1. For the case of working agent melting without a developed convection in the liquid phase of heat accumulator

$$\frac{dT_j}{d\tau} = \frac{1}{(c\rho\delta)_j} \left[ q_{REE} + \alpha_{amb} (T_{amb} - T_{amb}) + \frac{\lambda_1}{\xi} (T_{cr} - T_j) \right], \quad (1)$$

$$\frac{d\xi}{d\tau} = \frac{\frac{1}{2} c_1 \rho_1 \xi \frac{dT_j}{d\tau} + \frac{\lambda_1}{\xi} (T_{cr} - T_j)}{c_1 \rho_1 \left( \frac{1}{2} T_{cr} - T_j \right) - c_2 \rho_2 (T_{cr} - T_{2R0}) \frac{\xi - R}{\xi_0 - R} - \rho_2 r}. \quad (2)$$

2. For the case of working agent melting with a developed convection in the liquid phase of heat accumulator

$$(c\rho\delta)_j \frac{dT_j}{d\tau} = q_{PEA} + \alpha_{amb} (T_{amb} - T_{amb}) + \alpha_{cr} (T_1 - T_j), \quad (3)$$

$$c_1 \rho_1 \xi \frac{dT_1}{d\tau} = \alpha_j (T_1 - T_j) + \alpha_{cr} (T_{cr} - T_1), \quad (4)$$

$$\frac{d\xi}{d\tau} \left[ c_2 \rho_2 \left( \frac{-2 \cdot n (T_{cr} \cdot R - T_{2R0} \cdot R) + \xi (T_{2R0} - T_{cr})}{(n+1)(\xi_0 - R)} \right) + r \rho_2 \right] = \alpha_{cr} (T_1 - T_{cr}). \quad (5)$$

3. For the case of working agent solidification without a developed convection in the liquid phase of heat accumulator

$$\frac{dT_j}{d\tau} = \frac{1}{(c\rho\delta)_j} \left[ \alpha_{amb} (T_{amb} - T_j) + \frac{\lambda_2 (T_{cr} - T_j)}{\xi} \right], \quad (6)$$

$$\frac{d\xi}{d\tau} = \frac{\lambda_2 (T_{cr} - T_j) - q_{TEB} (R - \xi)}{\rho_1 r - \frac{1}{2} c_2 \rho_2 (T_j - T_{cr}) - c_1 \rho_1 (T_{1R0} - T_{cr}) \frac{R - \xi}{\xi_0 - R}}. \quad (7)$$

4. For the case of working agent solidification with a developed convection in the liquid phase of heat accumulator

$$(c\rho\delta)_j \frac{dT_j}{d\tau} = \alpha_{amb} (T_{amb} - T_j) + \alpha_{cr} (T_1 - T_j), \quad (8)$$

$$c_1\rho_1\xi \frac{dT_1}{d\tau} = \alpha_j (T_1 - T_j) + \alpha_{cr} (T_{cr} - T_1), \quad (9)$$

$$\frac{d\xi}{d\tau} \left[ c_2\rho_2 \left( \frac{-2 \cdot n (T_{cr} \cdot R - T_{2R0} \cdot R) + \xi (T_{2R0} - T_{cr})}{(n+1)(\xi_0 - R)} \right) + r\rho_1 \right] = \alpha_{cr} (T_1 - T_{cr}) - q_{TEB}. \quad (10)$$

In relations (1) – (10),  $c_i$ ,  $\rho_i$ ,  $\lambda_i$  are heat capacity, density and thermal conductivity of the liquid and solid phase of working agent, where index 1 corresponds to the liquid phase, and index 2 – to the solid phase of working agent;  $\tau$  is time;  $q_{REE}$  is the amount of heat released by REE element per unit time and falling at unit area of the end surface of a container with heat accumulator;  $\alpha_{amb}$  is coefficient of heat transfer to the environment,  $T_j$  is the bulk temperature of device metal jacket (the heat spent on heating or cooling of REE element due to its small value as compared to the heat accumulated by working agent, is ignored or taken into account in total heat capacity of metal jacket; this assumption allows taking the value of  $T_{amb}$  as the temperature of REE element);  $T_{amb}$  is ambient temperature;  $r$  is working agent melting heat;  $R$  is working agent layer thickness;  $\xi$  is phase interface;  $\alpha_j$ ,  $\alpha_{cr}$  are coefficients of heat transfer from the jacket to liquid and from the phase interface to liquid;  $T_1$  is the average temperature of the liquid phase;  $\tau_0$ ,  $\xi_0$  are the time and melt thickness whereby an intensive motion of convective currents starts, and temperature field in the liquid phase practically disappears;  $T_{2R}$ ,  $T_{2R0}$  are temperatures at  $x=R$  at any moment of time  $\tau$  and at  $\tau = \tau_0$ , respectively,  $\xi_0$  is melt thickness at  $\tau = \tau_0$ ;  $\tau_0$  is time whereby a linear change in temperature  $T_{2R}$  with time starts to be observed;  $n$  is parameter determined experimentally [4];  $q_{THERMOPILE}$  is the amount of heat removed per unit time by thermopile and falling at unit area of the end surface of a container with heat accumulator.

Thermopile calculation was done on the basis of a standard procedure with the use of application software package “Thermoelectric system calculation” (manufacturer – OJSC Kryotherm, Saint-Petersburg) [8]. From the analysis of  $q_{THERMOPILE}$  values equivalent to thermopile cooling capacity, the geometric dimensions of thermoelements contained in a thermopile, the value of supply current, and the electric power consumption were determined.

### **Results of a numerical experiment with cooling system for REE elements working in the intermittent heat release mode**

Results of a numerical experiment with the developed model of cooling device are given in Figs.3 – 10. Here, we show the time dependences of jacket temperature variation upon melting of agent, as well as the time dependences of phase interface coordinate for different scattering powers of REE element (Fig. 3 – 4), different fillers (Fig. 6 – 7), and the duration of full melting of working agent versus heat release power of REE element (Fig. 8). Fig. 5 shows for comparison the temporal variation of jacket temperature with the use of melting agent and natural air heating. Similar data for cooling mode are given in Figs.11 – 16.

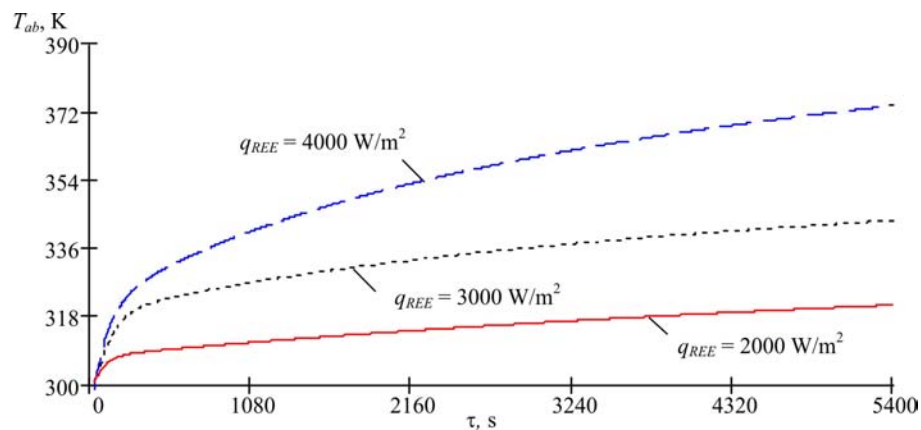


Fig. 3. Time dependence of jacket temperature upon melting of agent (paraffin) without liquid phase convection,  $(c\rho\delta)_j = 2 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$   $R = 0.03 \text{ m}$ .

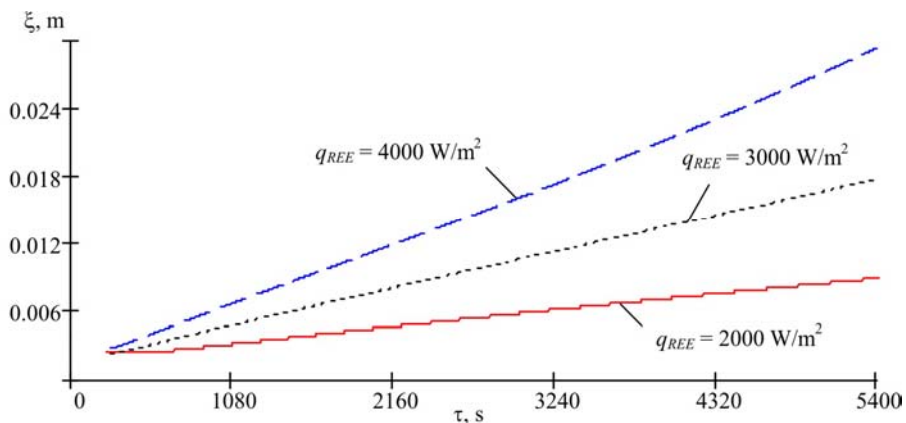


Fig. 4. Time dependence of phase interface coordinate upon melting of agent (paraffin) without liquid phase convection,  $(c\rho\delta)_j = 2 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$ ;  $R = 0.03 \text{ m}$ .

Calculations were made with the following input data: working agents – paraffin ( $\rho_1 = 760 \text{ kg/m}^3$ ,  $\rho_2 = 780 \text{ kg/m}^3$ ,  $c_1 = 2680 \text{ J/kg}\cdot\text{K}$ ,  $c_2 = 2350 \text{ J/kg}\cdot\text{K}$ ,  $\lambda = 0.27 \text{ W/m}\cdot\text{K}$ ,  $r = 156 \cdot 10^3 \text{ J/kg}$ ,  $T_{cr} = 316 \text{ K}$ ), elaidic acid ( $\rho_1 = 850 \text{ kg/m}^3$ ,  $\rho_2 = 860 \text{ kg/m}^3$ ,  $c_1 = 2180 \text{ J/kg}\cdot\text{K}$ ,  $c_2 = 1550 \text{ J/kg}\cdot\text{K}$ ,  $\lambda = 0.16 \text{ W/m}\cdot\text{K}$ ,  $r = 214 \cdot 10^3 \text{ J/kg}$ ,  $T_{cr} = 318 \text{ K}$ ), nickel nitrate ( $\rho_1 = 1980 \text{ kg/m}^3$ ,  $\rho_2 = 2050 \text{ kg/m}^3$ ,  $c_1 = 2140 \text{ J/kg}\cdot\text{K}$ ,  $c_2 = 1800 \text{ J/kg}\cdot\text{K}$ ,  $\lambda = 0.56 \text{ W/m}\cdot\text{K}$ ,  $r = 155 \cdot 10^3 \text{ J/kg}$ ,  $T_{cr} = 329.7 \text{ K}$ ),  $T_{amb} = 293 \text{ K}$ ,  $\alpha_{amb} = 10 \text{ W/K}\cdot\text{m}^2$  (except for cases when the value of  $\alpha_{amb}$  is indicated directly in captions to plots),  $\xi_0 = 0.001 \text{ m}$ ;  $\tau_0 = 20 \text{ s}$ ,  $\alpha_j = 20 \text{ W/K}\cdot\text{m}^2$ ,  $\alpha_{cr} = 20 \text{ W/K}\cdot\text{m}^2$ .

The calculated dependences define that jacket temperature and the time of working agent melting vary with the value of thermal load on cooling device ( $q_{REE}$ ), the type of working agent, as well as the conditions of heat exchange with the environment. In the absence of convective fluxes in the liquid phase, the process of heat exchange is the nonsteady-state heat conduction, and the device jacket temperature is constantly increasing. The rate of its increase is a function of heat input ( $q_{REE}$ ), layer thickness and agent thermal conductivity.

According to plots shown in Figs. 3–4, the increase in  $q_{REE}$  value increases considerably the temperature of the jacket and REE element, as well as agent melting rate (for instance, after 1.5 hours of REE element operation, with a change in its scattering power from 2000 to 4000  $\text{W/m}^2$ , the jacket temperature rises from 320 to 372 K, and melting rate grows from  $1.48 \cdot 10^{-6} \text{ m/s}$  to  $5.5 \cdot 10^{-6} \text{ m/s}$ ).

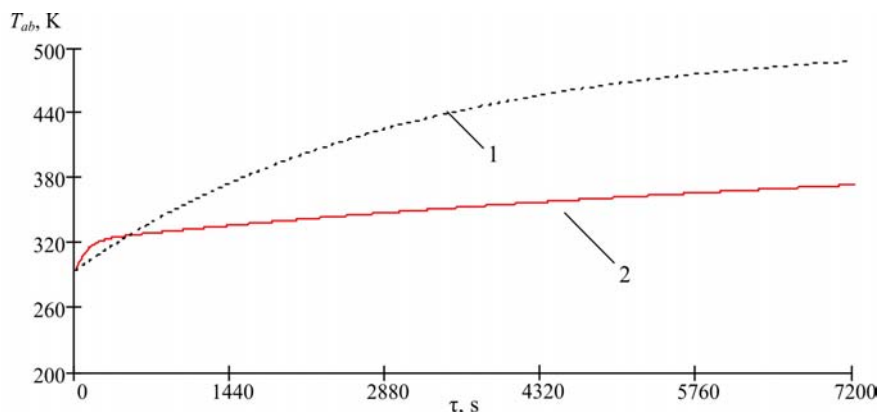


Fig. 5. Time dependence of jacket temperature upon melting of agent (paraffin) without liquid phase convection  $(c\rho\delta)_j = 2 \cdot 10^3 \text{ J}/(\text{m}^2 \cdot \text{K})$ ;  $R = 0.03 \text{ m}$ ,  $q_{REE} = 2000 \text{ W}/\text{m}^2$ ,  
 1 – use of natural air cooling with  $\alpha_{amb} = 5 \text{ W}/\text{m}^2 \cdot \text{K}$ ,  
 2 – use of cooling system with working agent – nickel nitrate.

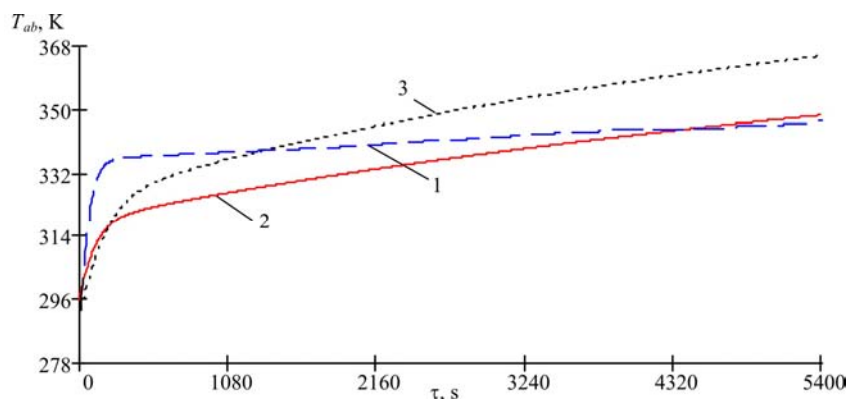


Fig. 6. Time dependence of jacket temperature upon melting of various heat accumulators without liquid phase convection,  $(c\rho\delta)_j = 2.5 \cdot 10^3 \text{ J}/(\text{m}^2 \cdot \text{K})$ ,  $R = 0.03 \text{ m}$ ,  $q_{REE} = 3500 \text{ W}/\text{m}^2$ . 1 – nickel nitrate, 2 – paraffin, 3 – elaidic acid.

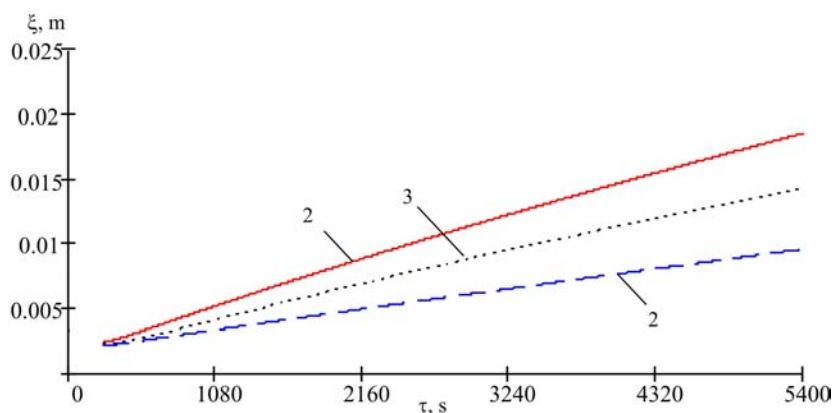


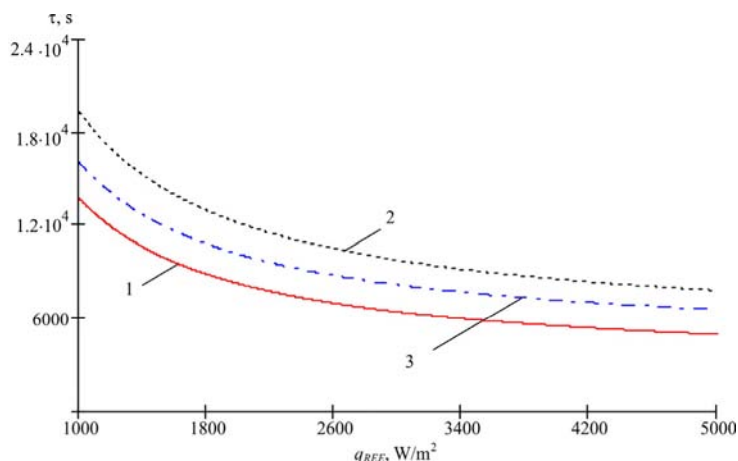
Fig. 7. Time dependence of phase interface coordinate upon melting of various heat accumulators without liquid phase convection,  $(c\rho\delta)_j = 2.5 \cdot 10^3 \text{ J}/(\text{m}^2 \cdot \text{K})$ ,  $R = 0.03 \text{ m}$ ,  $q_{REE} = 3500 \text{ W}/\text{m}^2$ . 1 – nickel nitrate, 2 – paraffin, 3 – elaidic acid.

The rise in device jacket temperature is also related to increase in thermal resistance of working agent liquid phase, which grows with enlargement of melted layer. This proves the necessity of taking steps for reducing the layer of agent liquid phase between REE element and phase interface.

Also, the temperature of REE element while in operation will be affected by selection of suitable working filler. Calculations were made for the case of using as such nickel nitrate, paraffin and elaidic acid (Figs. 6 – 7).

According to research results, the best results for given conditions were obtained with the use of nickel nitrate as a filler. According to dependences shown in Fig. 6, for the case of using nickel nitrate as a working agent the temperature of device jacket is most stable, and melting rate is the lowest. First of all, it is due to its higher thermal conductivity which is almost twice that of paraffin and 3 fold that of elaidic acid. Thus, a reduction of temperature growth rate (i.e. its stabilization) can be achieved by increasing the effective thermal conductivity of agent. One of the methods for increasing the effective thermal conductivity of agent is the use of various fillers. Thus, for instance, one can use metal grit, various kinds of finning or porous structures.

Fig. 8 shows the plots of full melting time of various fillers versus the dissipation power of REE element, which corresponds to its stable operation time. Here, the longest-running melting in the range of powers 1000 to 5000 W/m<sup>2</sup> is inherent in nickel nitrate, which is accounted for by its higher temperature and heat of melting, as well as by the value of thermal conductivity coefficient.



*Fig. 8. Dependence of full melting time of various heat accumulators on heat release power of REE element per unit area without liquid phase convection,  $(cp\delta)_j = 2.5 \cdot 10^3 \text{ J}/(\text{m}^2 \cdot \text{K})$ ;  
 $R = 0.03 \text{ m}$ . 1 – paraffin, 2 – nickel nitrate, 3 – elaidic acid.*

The process of agent melting is essentially affected by the presence of convective fluxes in its liquid phase. This case corresponds to arrangement of element on the lower end surface of a container with working agent and heat input from below with respect to heat accumulator. According to Figs. 9 – 10, for paraffin the convective fluxes start to have a considerable impact in 19 – 20 minutes after the start of melting process, which corresponds to melt thickness 0.009 – 0.01 m. From said moment for a developed convection in the agent liquid phase the process of melting is intensified. Consequently, the rate of travel of phase interface is increased, and temperature rise of cooling device jacket is retarded. As it follows from the plots in Fig. 9, in 1.5 hours after the beginning of melting process the temperature of device jacket with convection in the liquid phase of heat accumulator will be 12 K lower than without convective fluxes. At the same time, according to dependences represented in Fig. 10 the time of full melting of working agent with convection in the

liquid phase is somewhat lower than without. Under the above circumstances the time of full melting of agent in the former case is 78 min, and the latter case – 90 min. Said fact should be taken into account in the design of heat removal system in terms of increasing the amount of heat accumulator in a container when arranging REE element on its lower end surface.

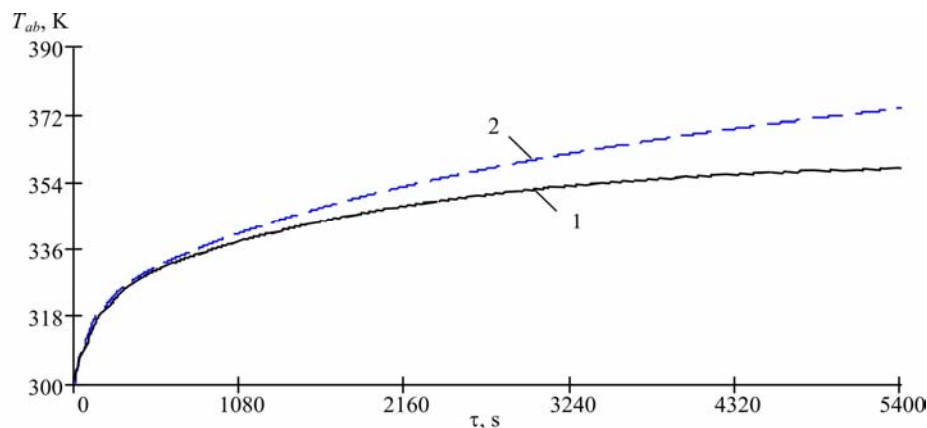


Fig. 9. Time dependence of jacket temperature upon melting of agent (paraffin) with (1) and without (2) liquid phase convection,  $(c\rho\delta)_j = 2 \cdot 10^3 \text{ J}/(\text{m}^2 \cdot \text{K})$   
 $R = 0.025 \text{ m}$ ,  $q_{REE} = 4000 \text{ W}/\text{m}^2$ .

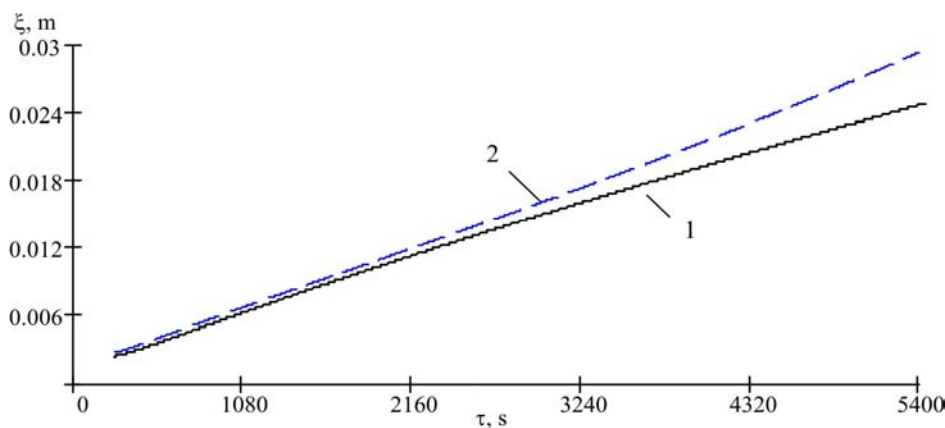


Fig. 10. Time dependence of phase interface coordinate upon melting of agent (paraffin) with (1) and without (2) liquid phase convection,  $(c\rho\delta)_j = 2 \cdot 10^3 \text{ J}/(\text{m}^2 \cdot \text{K})$ ,  
 $R = 0.025 \text{ m}$ ,  $q_{REE} = 4000 \text{ W}/\text{m}^2$ .

Figs. 11 – 15 show dependences of jacket temperature from the side of a contact to thermopile and phase interface upon solidification of a filler for various values of thermopile cooling capacity, as well as for conditions when agent cooling and solidification is due to natural heat exchange with the environment. As can be seen from the plots, the time of cool down of working agent and device jacket with the use of a thermopile is several fold less than the time of their cool down with a natural heat exchange with the environment (for paraffin this ratio at  $q_{THERMOPILE} = 2000 \text{ W}/\text{m}^2$  and  $\alpha_{amb} = 10 \text{ W}/(\text{m}^2 \cdot \text{K})$  made 2 times). Hence it follows that the use of a thermopile relieves the existing restrictions to operating cycle duration of REE element and the duration of pause between its actuations. Therefore, whereas in case of natural heat exchange between cooling device jacket and the environment the operating period of REE element must have been considerably less than the “pause”, with the use of a thermopile the time between two consecutive cycles of REE operation may be considerably reduced. In so doing, the quickest process of substance cooling and solidification



occurs with the use of paraffin and nickel nitrate as fillers (from Fig. 14 – 15, where studies were performed for paraffin, nickel nitrate, palmitinic and elaidic acids). The former is used due to the lowest temperature and melting heat, the latter – due to higher thermal conductivity coefficient.

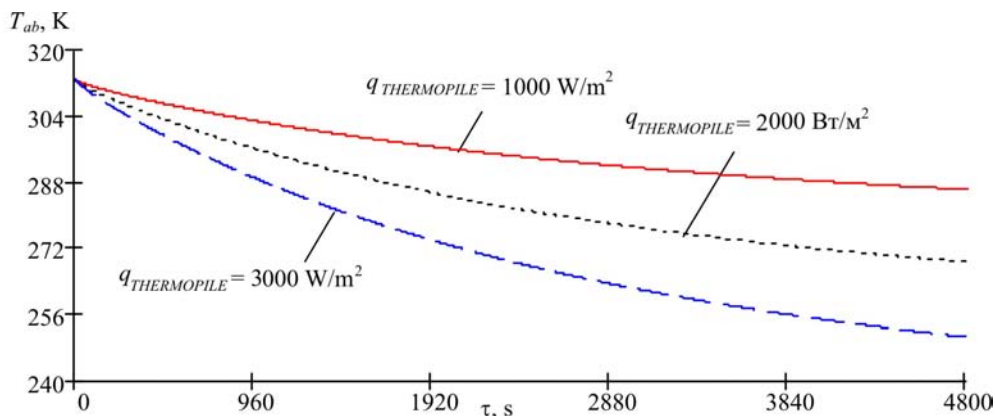


Fig. 12. Time dependence of phase interface coordinate upon solidification of agent (paraffin) ( $cp\delta_j = 6.5 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$ );  $R = 0.025 \text{ m}$ .

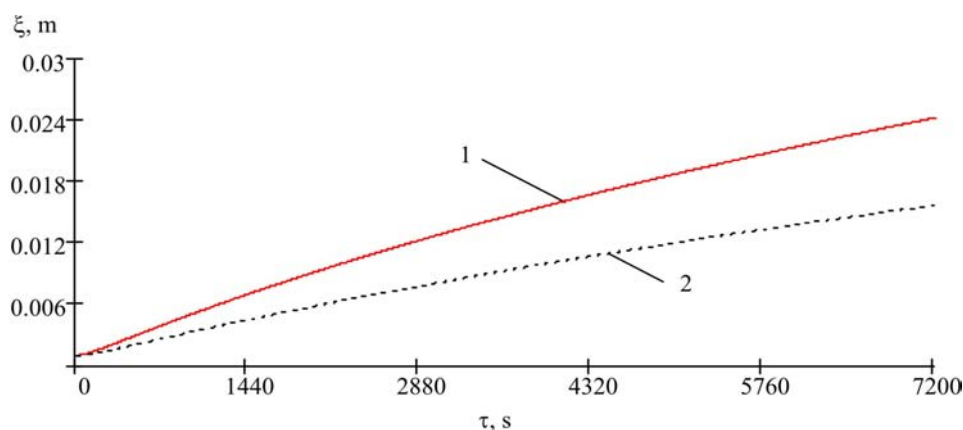


Fig. 13. Time dependence of phase interface coordinate upon solidification of agent (paraffin), ( $cp\delta_j = 6.5 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$ );  $R = 0.025 \text{ m}$ . 1 – with the use of thermopile with  $2000 \text{ W/m}^2$  2 – with the use of natural air cooling due to heat exchange with environment ( $\alpha_{amb} = 10 \text{ W/m}^2 \cdot \text{K}$ ).

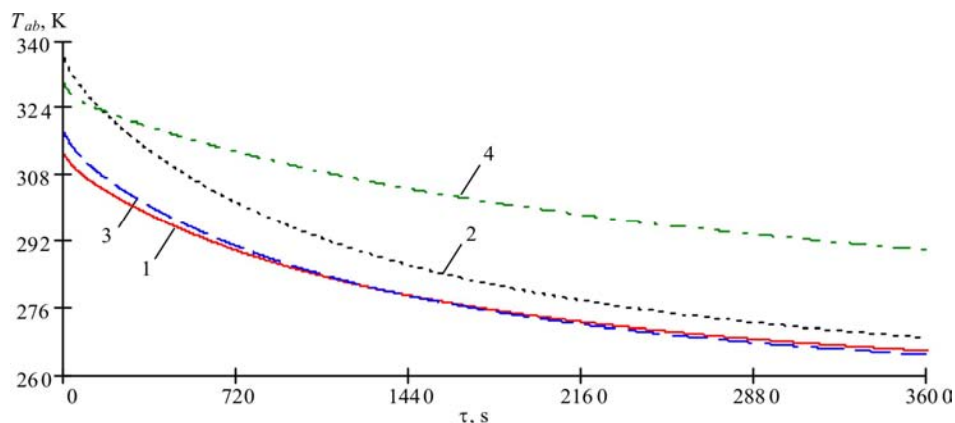


Fig. 14. Time dependence of jacket temperature upon solidification of various fillers, ( $cp\delta_j = 2.1 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$ );  $R = 0.02 \text{ m}$ ,  $q_{THERMOPILE} = 1500 \text{ W/m}^2$ . 1 – paraffin, 2 – palmitinic acid, 3 – elaidic acid, 4 – nickel nitrate.

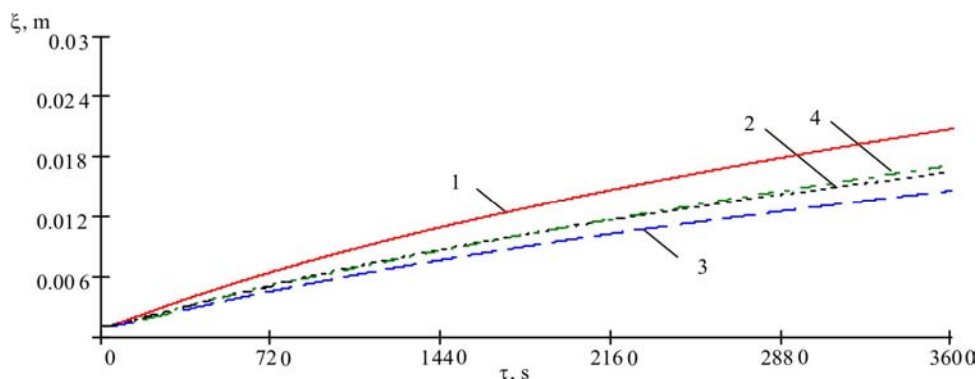


Fig. 15. Time dependence of phase interface coordinate upon solidification of various fillers,  $(cp\delta)_j = 2.1 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$ ;  $R = 0.02 \text{ m}$ ,  $q_{\text{THERMOPILE}} = 1500 \text{ W/m}^2$ .  
1 – paraffin, 2 – palmitinic acid, 3 – elaidic acid, 4 – nickel nitrate.

The duration of agent solidification process can be reduced considerably with the use of the additional heat removal from the lateral surface of a container with the agent. According to calculated data (Fig. 1b), the use of the additional heat pickup with  $q_{\text{THERMOPILE}} = 6000 \text{ W/m}^2$  with the main  $q_{\text{THERMOPILE}} = 1500 \text{ W/m}^2$  will allow reducing the time of full solidification, for instance, for paraffin to 1200 s, nickel nitrate to 2000 s, palmitinic acid - to 2400 s. In so doing, in the case of the additional heat pickup from the lateral surface, when the values of thickness, length and width of sections with melting fillers are comparable, a direct calculation according to Eqs. (1) – (5), (6) – (10) is unacceptable. In this case, velocity addition principle is employed, which is stated, for instance, in [9].

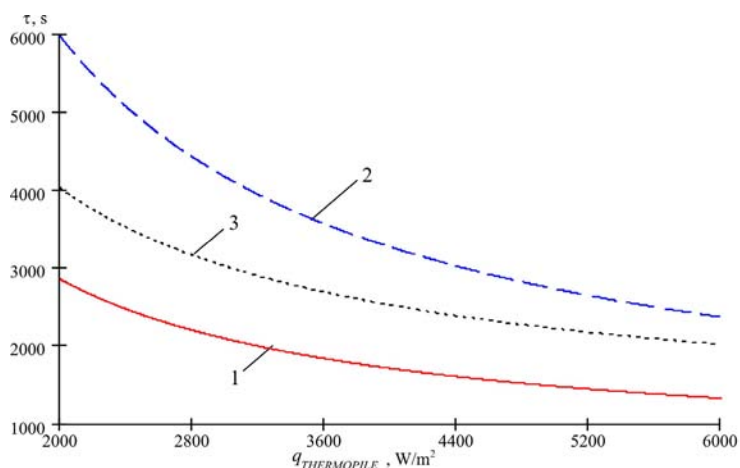


Fig.16. The time of full solidification of working agent with the use of the additional heat pickup from the lateral surface of a container versus thermopile power per unit area,  $(cp\delta)_j = 2.5 \cdot 10^3 \text{ J/(m}^2 \cdot \text{K)}$ ;  $R = 0.02 \text{ m}$ .  
1 – paraffin, 2 – palmitinic acid, 3 – nickel nitrate.

According to this method, at first by means of one-dimensional solutions the thickness of working agent layer and the temperature of jacket in the directions of  $x$ ,  $y$ ,  $z$  are determined on condition that melting or solidification rates are independent of each other. Then the duration of melting or solidification of the whole mass in a container is calculated based on relationship

$$\frac{1}{\tau_n} = \frac{1}{\tau_x} + \frac{1}{\tau_y} + \frac{1}{\tau_z} \quad (11)$$

where  $\tau_n$  is duration of agent melting or solidification in a container;  $\tau_x, \tau_y, \tau_z$  are durations of melting or solidification in the direction of axes  $x, y, z$  in the absence of melting or solidification effect in the directions  $y, z; x, z$  and  $x, y$ , respectively.

By the known value of  $\tau_n$  the temperature of device jacket is determined by means of one-dimensional solutions. As long as the influence of container size on the temperature of its jacket is less than on the thickness of melted layer, the resulting value of jacket temperature for a one-dimensional problem will allow estimating the limit temperature conditions of container jacket, hence, of cooled REE element.

## Conclusions

As a result of investigations, the following conclusions can be made:

1. One of the efficient methods for heat removal from REE elements working in the intermittent heat release mode is a method based on the use of melting working agents. The main disadvantage of this method is a restriction related to the necessity of assuring melting process during the entire operation period of REE.
2. A cooling system for REE elements is proposed enabling one to expand the duration of their operation period due to the use of the additional heat removal from melting agents via a thermopile.
3. A mathematical model of cooling system is developed, realized by solving Stephan's problem with the use of Leybenzon' approximate method, the principle of which lies in selection of such functions of the liquid and solid phase temperature variation that would meet the initial and boundary conditions. The thus selected functions are substituted into phase matching condition, and the resulting differential equation is solved for phase interface coordinate.
4. As a result of solving the problem of melting (solidification) of agent, the time dependences of temperature variation of cooling system jacket, as well as phase interface coordinates were obtained. Said dependences strongly depend on heat scattering of REE element, the types of working fillers, thermopile cooling capacity, and the environmental conditions.
5. It was established that after 1.5 hours of REE element operation with a change in its scattering power
6. from 1000 to 3000 W/m<sup>2</sup> with the use of paraffin the jacket temperature is increased from 317 to 367 K, and melting rate – from 10<sup>-6</sup> m/s to 3.7·10<sup>-6</sup> m/s.
7. The temperature of REE element while in operation is affected by selection of suitable working filler. The best agents in this respect will be those which, all other conditions being equal (melting temperature, melting heat, heat capacity, etc), have high values of thermal conductivity coefficient.
8. One of the methods for increasing the effective thermal conductivity coefficient can be the use in the working agent of various types of fillers (metal grit, various kinds of finning, porous structures).
9. On arrangement of REE element on the lower end surface of a container with working agent, melting process will be considerably affected by the presence of convective fluxes in its liquid phase. Under these conditions the temperature of REE element will be lower, but on the other hand the time of full melting of working agent will be reduced, which must be taken into account in the design of cooling system.

10. As a result of investigation of heat exchange at solidification of working agents it was established that the use of a thermopile reduces considerably the time of working agent solidification. For paraffin at  $q_{THERMOPILE} = 2000 \text{ W/m}^2$  its value is almost half as much as in the case of natural heat exchange with the environment at  $\alpha_{amb} = 10 \text{ W/(m}^2 \cdot \text{K)}$ .
11. For the intensification of the process of cooling and solidification of working agents it is worthwhile to realize heat pickup by the additional thermopiles arranged on the lateral surface of a container with working agent.
12. In the case of the additional heat pickup from the lateral surface, when the values of thickness, length and width of sections with melting fillers are comparable, a direct calculation according to Eqs. (1) – (5), (6) – (10) is unacceptable. In this case, velocity addition principle in conformity with Eq. (11) is employed.

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