STUDY OF THE HEAT EXCHANGE PROCESSES IN HEAT STORAGES WITH SHAPE-STABLE COMPOSITE PHASE-TRANSITIONAL MATERIALS

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Abstract

In this paper study of the heat exchange processes in heat storages (HS) with a new structure of melting working substance, peculiar to shape-stable composite materials, has been presented. The heat exchange processes have been experimentally verified in the HS of new types. Engineering HS computation procedure has been developed and compared with the conventional integral one [3]. On this basis the computation procedure of thermal conditions for radio-electronic equipment(REE), consisting of energy source (ES) and the HS, has been developed. Recommendations regarding the selection of the HS design parameters have been presented.

KEYWORDS

Heat storage (HS), phase-transitional material (PTM)**,** unpackage HS, shape-stable PTM, heat storing material.

INTRODUCTION

Heat storages (HS), in which shape-stable composite phase-transitional materials (PTM) are used, are actively being integrated in systems of cooling and thermal protection of radio-electronic equipment under the conditions of extreme heat loading. Their application is promising for energy saving thermal technologies, for heating accommodations, for household use, and in medicine.

The present paper is the continuation of the report presented at the VI Minsk International Seminar [1].

VERIFYING EFFICIENCY OF APPLYING HS OF NEW TYPES AND ITS MATHEMATICAL MODEL

The efficiency of HS application with the shape-stable PTM will be shown on a concrete example.

General view of the powerful ES, set on the HS, is presented in Fig. 1. The thermal contact between the ES and the HS is carried out using heat-conductive compound 137-182 TU 6-02-1-405-86 (137-182 TU 6-02-1-405-86).

The power of the ES is up to 400 W. The HS represents a ribbed radiator made of aluminium alloy for extending the heat exchange surface between the PTM and metallic part of the construction; the cavities between ribs are filled with heat-accumulating material B-TAM-50 TC1-595-53-592-200 (V-TAM-50 TU 1-595-53-592-200) with melting temperature of 52–55 °C. The ES operates during sessions lasting up to (10-12) minutes with a subsequent long pause. The temperature on the cooled ES heat sink should not exceed 90 °C. Usually for this type of ES active air or liquid cooling systems are used (here thermal flow density reaches up to $q = 5\cdot10^4$ W/m^2). In this case, through constructive considerations it is favourable to apply a passive heat-accumulating system using latent heat of phase transfer, PTM thermal capacity and the radiator construction mass. The general form of the HS with shape-stable PTM which does not require hermetic sealing the volume of the melting or hardening working substance, is described in the patent [1].

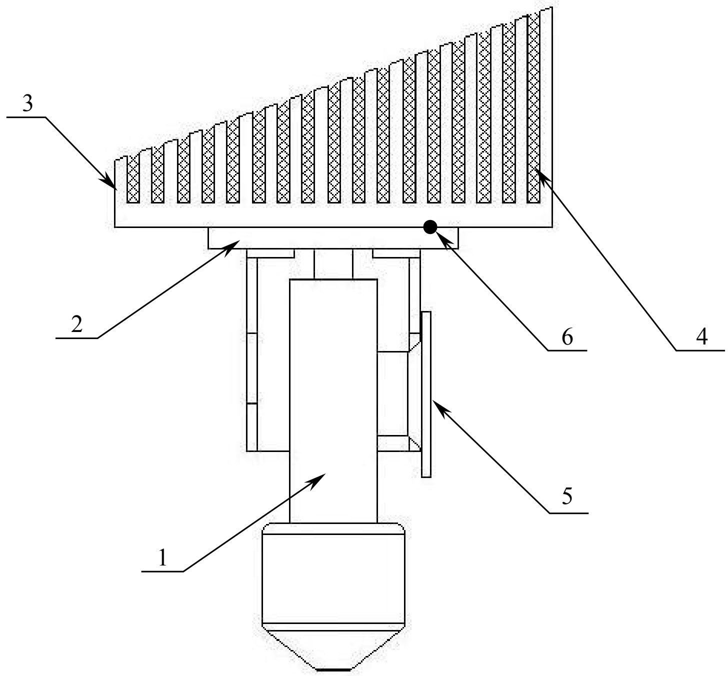

Fig. 1. General view of energy source (ES), set on the HS with the PTM: 1– ES, 2 – heat sink for ES, 3 – HS, 4– PTM, 5 – flange for mounting the ES to REE, 6 – contact plane between HS and ES heat sink, where the power is dissipated

The results of thermal tests of such an ES with ribbed radiator, in whose cavities between the ribs it succeeded in placing 0.19 kg of the shape-stable PTM, are presented in Fig. 2. As it can be seen from Fig. 2, the ES temperature has reached the acceptable value in 6 minutes.

It has shown, that the effect from applying such a HS is obvious, but the amount of PTM mass should be enlarged. As a result, a new task has arisen. It regarded the determination of needed PTM mass, size of cavities between the ribs, ES and HS temperatures depending on time and other parameters. All this became the theme of the given study.

In the book [3] and other later publications [5] the developed engineering methods of computing the heat conditions for the HS with ES were presented, but their applicability for calculating the heat conditions for HS with shape-stable PTM had not been verified. Therefore for simplicity, we tried to use one of the HS computation procedures – integral approximate calculating melting and hardening processes with determination of moving interphase boundary [2] and another, more rough studied in this paper, computation procedure, which can be conditionally called heat capacity or enthalpy. The latter takes into account total mass thermal capacity of the whole HS as a united isothermal substance, in which the PTM mass and construction of metal part of the HS under some conditions can have almost the same temperature.

Such an assumption for the HS thermal model comes from our experiments [1] and the results of study of some shape-stable PTM thermo-physical properties [4]. They were conducted on thin plates (up to 10 mm thick) by means of the method of high-speed measurement of the complex of thermophysical properties at monotonous heating of samples. It was difficult to determine directly from experiments values of thermal conductivities and latent heat of phase transfer because of low thermal conductivity of the PTM and variations of samples’ material composition through their volume. These values were determined by re-counting received values from total endothermic effect of the plate.

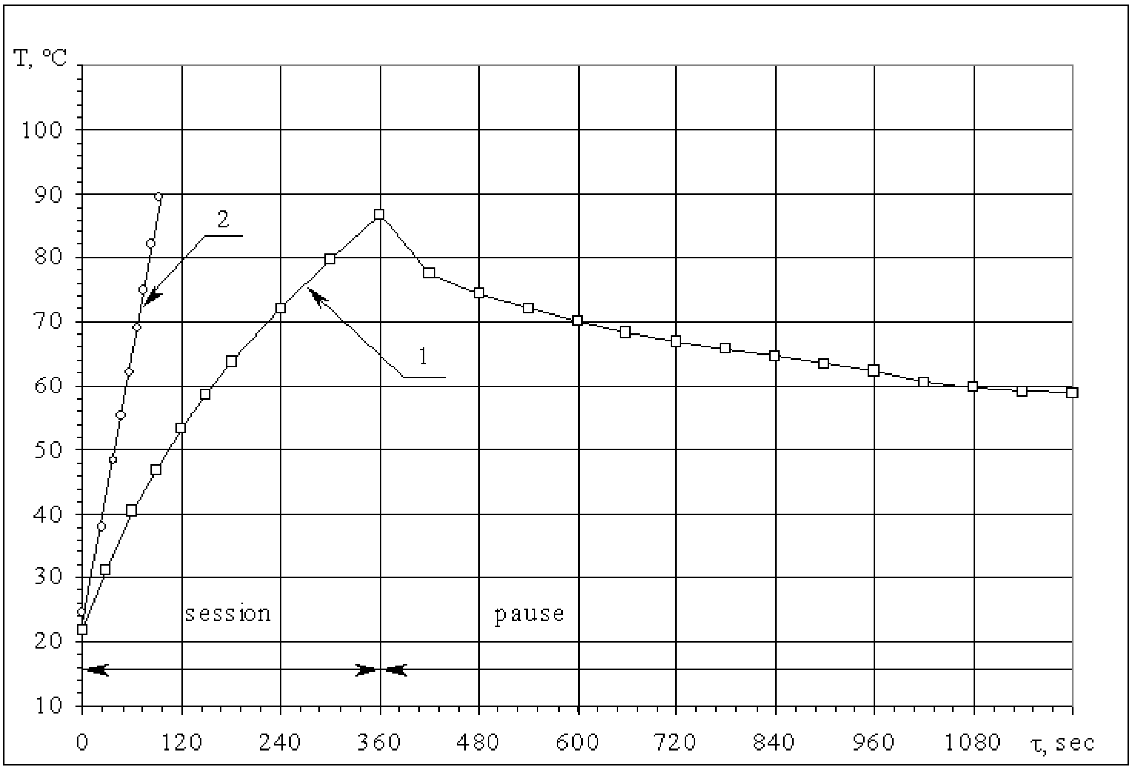

Fig. 2. The efficiency of applying HS with shape-stable PTM in comparison with a typical ribbed radiator: 1 – HS; 2 – radiator without PTM

Taking into account these phenomena and structural arrangement of the HS, which have the thickness of PTM layer between the nearest metal surfaces with high thermal conductivity (for example, ribs or honeycombs made of aluminium alloys) usually don't exceed 2–4 mm, it was concluded that the discrepancy of temperatures through the PTM volume can be neglected.

Such an assumption is better fulfilled at the low density of thermal flow from the ES, referred to the total area of contact between the PTM volume and the metal part of the HS structure (up to 3000–5000 W/m^2).

Then, the energy-conservation equation for the HS, as unified isothermal working substance, can be presented in the form of:

$$[C_e(T_{PTM})M_{PTM} + C_kM_k]\,(dT_{HS} / d\tau) = P_{HS} - \sigma_{HS \cdot env.}(T_{HS} - T_{env}) \tag{1}$$

where:

$C_e(T_{PTM})$ – specific mass thermal capacity of PTM in the HS volume, received from total endothermic effect in the selected temperature range, J/(kg·K);
T_{PTM} – average mass temperature of the PTM, K, °C;
M_{PTM} – the PTM mass, kg;
C_k; M_k – specific thermal capacity and the mass of the HS structure metal part, which contacts the PTM, J/(kg·K); kg;
T_{HS} – average mass temperature of the HS, K, °C;
T_{env} – environmental temperature, K, °C;
τ – time, s;
P_{HS} – the quantity of heat supplied by the energy source directly to the HS, W;
$\sigma_{HS \cdot env}$ – total thermal conductivity between the HS and environment, W/K.

If the experimental value of the endothermic effect in the vicinity of phase transfer temperatures is known, and also the values of specific thermal capacities of solid and liquid phases beyond the limits of this range, then in the same equation (1) instead of expression given in brackets we can use:

$$[(C_{sol} + r_{eff} / \Delta T_{cr} + C_{liq})m + C_k m_k] \qquad (2)$$

where:

C_{sol}, C_{liq} – specific thermal capacities of solid and liquid phases beyond the limits of the phase transfer temperatures, J/(kg·K);
r_{eff} – total endothermic effect in the vicinity of phase transfer temperatures, J/kg;
ΔT_{cr} – experimental value of temperature drop in the flat PTM layer in the vicinity of phase transfer temperatures.

Unlike the presented thermal capacity method, while applying the integral method [3], the value of latent melting heat is used r*,* J/kg, at constant phase transfer temperature ΔT_{cr}, K, °C.

REE THERMAL CONDITIONS COMPUTATION PROCEDURE

For computing the thermal conditions for the REE, containing the HS with shape-stable PTM, a typical mathematic model in the form of ordinary differential system with first-order differential equations has been used. In this system, equations of thermal balance for isothermal working substance for component parts of the REE, including the ES with the HS, recorded as (1) or (2), have been applied.

The system of working substances, which does not contain the HS, is presented in the form:

$$C_i \cdot m_i \cdot dT_i / d\tau = P_i + \sigma_{ic} \cdot (T_c - T_i) + \sum_{n=1, i \neq j}^{n} \sigma_{ij} \cdot (T_j - T_i), \qquad (3)$$

where:
C_i, m_i – specific thermal capacity and mass of isothermal substances;
$i \neq j$;
i – number of working substance;
n – amount of working substances;
σ_{ic} – thermal conduction between the substance *i* and environment;
σ_{ij} – full thermal conductions between substances *i* and *j*.

In this regard, the equation of thermal balance for the HS can be presented in the form of (1) or (2), in the balance of which the power scattered by the ES is included, or the ES is presented as a separated substance, interacting with the HS.

In Fig. 3 comparison of the results of experiment and calculation of thermal conditions for the ES and the HS, considering their heat interaction with the rest part of the REE is presented. During the session the ES with the HS was in the climate chamber at the temperature of 40 °C, during the pause – outside of the chamber at an ambient temperature of 22 °C.

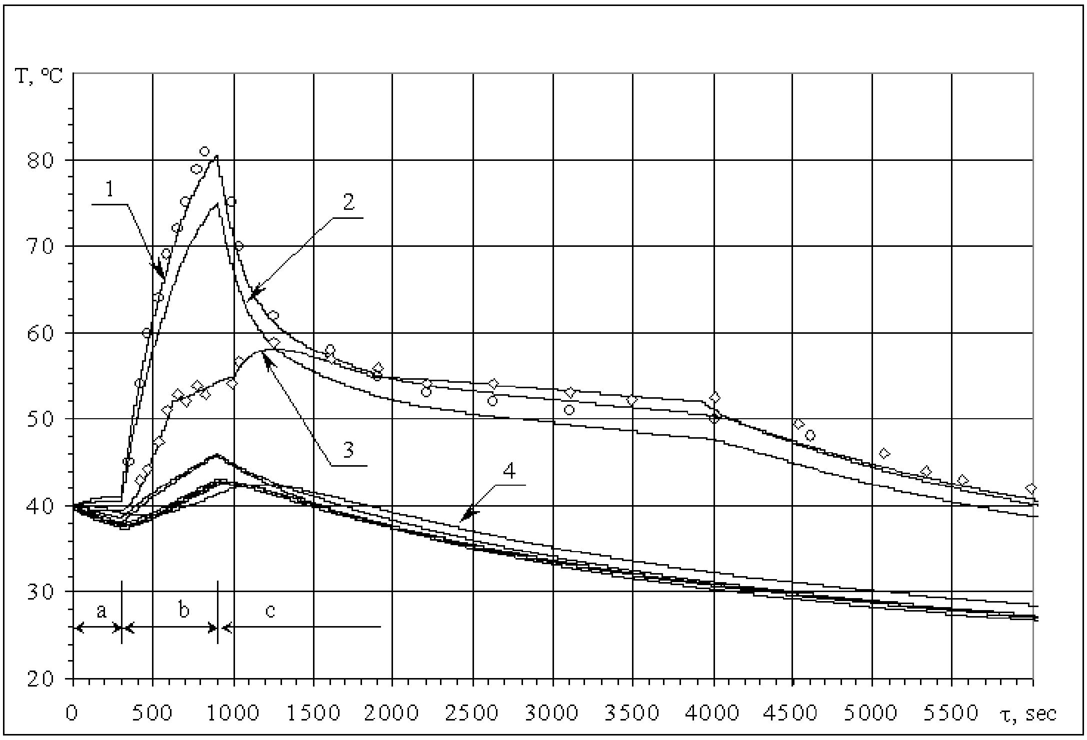

Fig. 3. The comparison of results of thermal conditions for the ES and the HS, running in session regime in the composition of REE container: ○ – experimental ES temperature values; □ – experimental HS temperature values; 1–4 – temperature values calculated using thermal capacity method, correspondingly for the ES; bracket for mounting the HS to the REE container; the HS case; other parts of the REE construction; a, b, c – correspondingly duration of the ES heating at 20 W; of the 300 W session on the ES, 400 W – for the rest part of the REE; of the pause

Here the power, scattered by the ES during the session, was 300 W, during the pause between the sessions was 20 W. The power of the rest of REE during the session was 400 W. From Fig. 3 one can see, that the experimental temperature values of the ES and the HS, on which 6 thermocouples were installed across the volume to determine the irregularity of the temperature field, coincide with the accuracy required for engineering computations. Here the attention should be paid to the fact that the noticeable difference between the ES and the HS temperatures was caused by the high resistance of thermal contact and by the high value of heat flow density between them. However, the assigned task was accomplished. For this purpose it was required to increase the PTM mass up to 0.4 kg instead of that disposed earlier (0.19 kg). And one more peculiarity lies in that the time for hardening and cooling the HS during the pause between sessions can be considerable, which should be considered in the engineering practice.

DEVELOPMENT OF RECOMMENDATIONS REGARDING THE SELECTION OF THE HS PARAMETERS

Considering these circumstances, additional studies of the HS at the densities of the supplied heat flows, peculiar for this method of energy storage, have been conducted. Apparently it is necessary to limit their values up to $(3–5)\cdot 10^3$ W/m^2. Studies were conducted on the ribbed HS.

The results of the experiments and calculations of the HS for power of 48 W, which corresponds to the heat flow density of about 300 W, are presented in Fig. 4. From that one can see that it is preferable to make calculations using the integral method [1], however, the heat capacity method is quite applicable in practice at a stage of the design calculations, when it is necessary to determine the required PTM amount and the pause period between the repeated sessions.

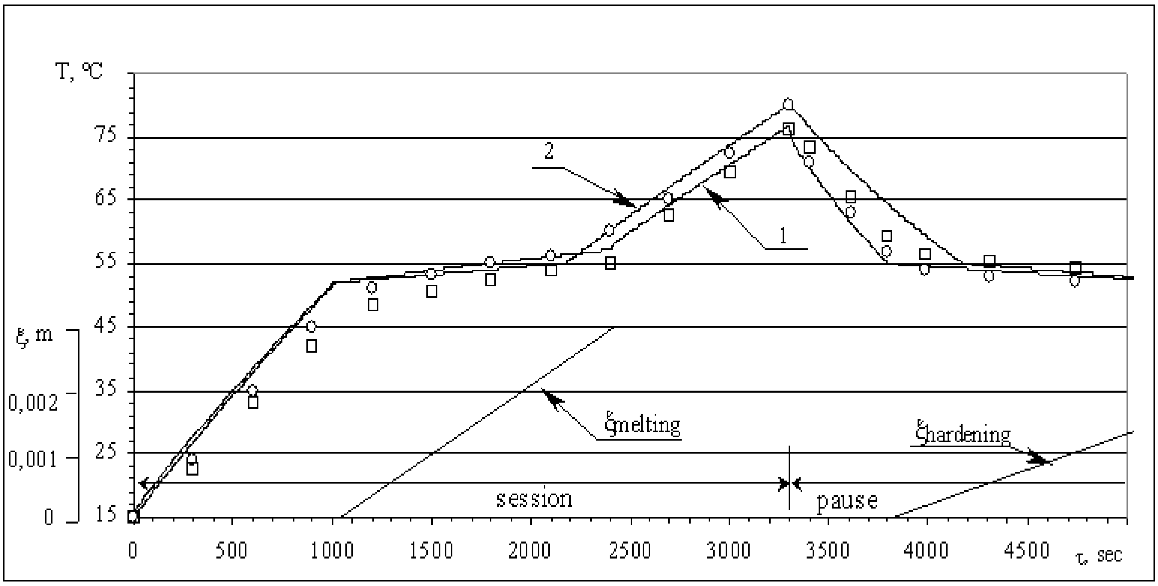

Fig. 4. Comparison of the integral and enthalpy methods of calculating the HS of ribbed type (P = 48 W): 1 – integral method [1], 2 – heat capacity method; □, ○ –experimental temperature values inside the PTM. The thickness of the cavity between the ribs – 0,006 m, the contact area of the PTM with the ribs – 0.164 m^2

The comparison of the calculating results with reference to V-TAM-50 by means of integral [2] and presented here heat capacity calculating method with adduced equivalent parameters have shown a good coincidence between themselves, which allowed to receive by calculation of the main characteristics, necessary for designing the HS.

The dependence of the admissible thickness of the PTM layer on the value of heat load, equal to the ratio of power, supplied to the HS, to the contact area between the PTM and the metal part of the HS structure, for different limit temperatures on the HS case is presented in Fig. 5. Here $R_{adm.}$ – half of the PTM layer thickness, limited by two neighbouring ribs (for honeycomb structure – half of the distance between the opposite walls of the flutes).

Using this dependence with the specified power, supplied to the HS, one can determine the rib pitch and rib height, and as for honeycomb structures - configuration and height of flutes, the cavities between which are filled with the PTM.

Computations, performed by the presented procedure have shown, that reliable thermal contact between the ES and the HS plays rather important role for providing necessary thermal conditions. In this regard it is necessary to watch that during the pauses between the adjacent cycles, the HS would have enough time to throw out stored energy into the environment.

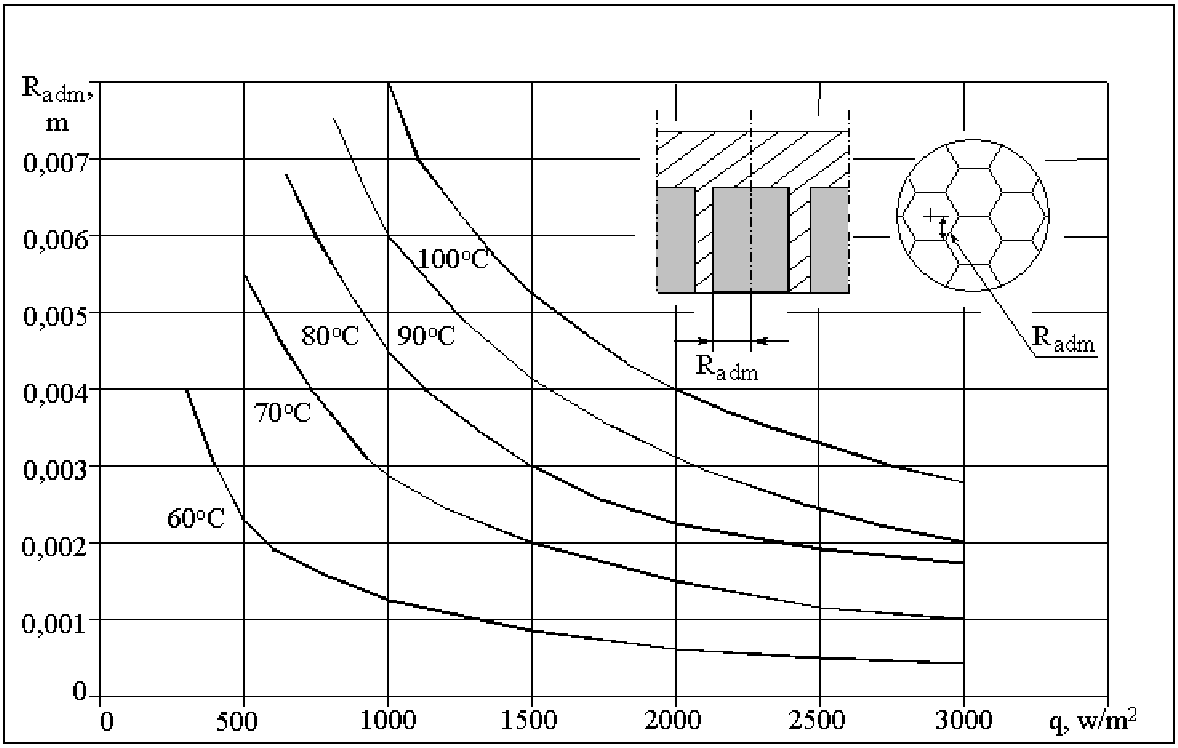

Fig. 5. Variation in thickness of the PTM layer from the value of the heat load for different allowable temperatures (PTM-V-TAM-50)

CONCLUSION

The study of the HS of new types, often called unpackaged, has been carried out and proposed here. This type of HS uses shape-stable phase-transitional composite material (PTM) as a melting working substance, which doesn't require hermetic encapsulation of the volume, whose structure and properties are different from the traditional ones.

This type of HS has been tested using the known integral computation method, developed by V. A. Alexeev earlier [3]. And with it, the authors have proposed simplified approach for solving the problems of thermal designing REE, consisting of HS for removal of peak thermal loads from a powerful energy source.

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