Aspects of modeling the magnetically controlled thermal accumulators for aerospace engineering

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Abstract. Approaches for creating magnetically controlled thermal accumulators for aerospace engineering based on thermomagnetic convection under the action of a magnetic field created by neodymium magnet under thermal conditions are discussed. The properties of thermal accumulating material (TM) containing magnetic particles are studied. To investigate the distribution of the temperature field it was used a contactless measurement method realized using a thermal imager. The formulation of the problem of mathematical modeling for a thermal control system with TM based on the finite integral transform method is carried out. It allows to study the distribution of temperature fields at design stage. The application of the effect of thermomagnetic convection makes it possible to intensify heat exchange in TM, which increases the efficiency of charge and discharge of TM. This approach is economically feasible and technologically adapted to aerospace technology.

1. Introduction

Today much attention is paid to the creation of "smart" materials that have manageable functional properties and are able to support the given parameters in different conditions. Particular importance in the technology of the "smart" materials creation can take materials that have thermoregulating properties. Thermoregulating materials can be widely used in aviation and space engineering. First of all, this is due to the need of effective thermoregulation of the internal area of aerospace equipment, which is associated with providing comfortable temperature for passengers and service staff, as well as saving the energy resources. Existing technological solutions are associated with the use of electric heaters, which have a decentralized arrangement; while at the desired periods of time there is their heating with thermal energy impact into the internal area, where the passengers and crew are located. Large volumes of internal area and power limitation of thermoregulation system do not allow providing the effective thermoregulation with creation of comfortable conditions. There were carried out studies in the work [1], and it was shown how the duration of airplanes flight affects the temperature modes inside the cabin. The authors found that the short flights had difficulties with creation of comfortable conditions. According to the authors, the solution is an improved model of the temperature mode. In order to obtain objective data related to temperature modes in aircraft cabins, in [2] there were temperature modes measured on mannequins in the full-scale 21-seat section of the aircraft cabin, and the measurements on mannequins were correlated with subjective estimates of the
thermal sensation of various parts of the body. The results of the studies [2] showed that local thermal sensations can be predicted using the mannequins.

To increase the efficiency of electric heating systems, there is a potential associated with the implementation of adaptive thermoregulation using thermal accumulators.

Taking into account the large internal volume of the airplanes’ cabin, it is necessary to use approaches related to the implementation of multifunctional electric heating systems containing a thermal accumulating buffer, which has adjustable heat conductivity. It will provide a higher sensitivity to the temperature inside the cabin and reduce the consumption of electrical energy for heating. It is reasonable to realize the thermal accumulating buffer using the magnetically controlled thermal accumulators in the mode of thermomagnetic convection [3]. For realization of the thermoregulation system based on thermal accumulating materials, it is necessary to consider technologies of thermal energy accumulating using nanomaterials.

In the article [4] there were shown studies of thermal conductivity of materials with a self-regulation effect in the modified material structure. Self-regulation of “magnetic graphene” improves the thermal conductivity of composites and epoxy resins. When testing the modified material using computer chips, the temperature was reduced by 10 °C compared to other materials. At the same time the authors [4] consider materials that do not have a phase transition, which reduces their efficiency while accumulation of thermal energy. There are questions arises about imparting magnetic properties to nanostructures. Functionalization of carbon nanotubes (CNTs) through magnetic nanoparticles was studied in works [5-6]. The effect of orientation and alignment of CNTs embedded in an epoxy polymer matrix under the influence of a magnetic field on the mechanical properties of obtained nanocomposite was investigated in [5]. The authors found that when alignment of CNTs occurs under magnetic field conditions, the properties of the obtained composites are superior to properties that have not been exposed by magnetic field. In work [6] there are investigated physicochemical mechanisms, under which positive charges ensure effective adsorption of negatively charged magnetic nanoparticles on the graphene surface by means of electrostatic interactions.

In [7], composites of thermoplastic polyurethane elastomer (TPU) / BNNSs (hexagonal boron nitride nanosheets) are made by combining modification and magnetic equalization. In order to impart magnetic properties to BNNSs, it was processed in the manner in which Fe₃O₄ particles were generated on the BNNS surface by oxidizing the aqueous suspension of Fe(OH)₂ at room temperature. The authors of the paper obtained thermal conductivity (TPU) / BNNSs at the level of 5.15 W m⁻¹ K⁻¹ at BNNSs of 30% by weight. In [8] another approach was used to create magnetically controlled 2D nanofiller. In [8], a surface modification of nano-networks of boron nitride (BNN) is used. For this purpose, after the polymerization reaction of BNN, redox polymerization of acrylamide occurs on the surface of already functional hydroxyl-functional BNN. Subsequently, magnetic iron oxide nanoparticles are introduced into the modified BNN by the chelating action of polyacrylamide. Finally, to ensure high-conductivity and magnet-sensitive nanocomposites, the functionalized Fe₃O₄ / BNN is dispersed in an epoxy matrix and aligned under an external magnetic field. Based on the results of thermal conductivity, the thermal transfer of nanocomposites increases to 0.37 W m⁻¹ K⁻¹, with only 10% of the functionalized Fe₃O₄ / BNN (at 25 °C) applied.

So, the main trend in improving the thermophysical properties of composites is associated with the assignment of magnetic properties to nanoscale materials. However, these researches are aimed at studying the properties of solidified composites. At the same time, it is possible to significantly improve heat transfer by using non-hardening materials with phase transitions in which thermomagnetic convection is possible. The problems that should be solved when creating thermoregulation systems with the use of thermal accumulators (TA) based on TM (thermal accumulating material) should include:

- to investigate the properties of thermal accumulating material containing carbon nanostructures with nickel-zinc ferrite;
- to develop the concept of mathematical modeling with the possibility to obtain analytical dependencies, which will allow quick organization of the prototyping the thermoregulation system.
2. Methods and materials
To produce magnetically controlled thermal accumulating material (TM) paraffin (P-2 (Lukoil, Russia)) and modified multi-walled carbon nanotubes (MWCNTs) of the “Taunit” series (NanoTechCenter, Tambov, Russia) were used. MWCNTs were mechanically activated with nickel-zinc ferrite 400HH Ni1-xZnxFe2O4 (NanoTechCenter, Tambov, Russia). Ni1-xZnxFe2O4 was preliminary dispersed to size of 2-4 μm in a ball mill for 60 minutes.

Modifying of paraffin by MWCNTs was performed via ultrasonic radiation and under the exposure of magnetic field (up to 1500 mT). The modifying of paraffin by obtained MWCNTs occurs during the phase transition of paraffin to the liquid state.

The obtained material was granulated in a pressing granulator to form the granules with the size range of 0.5 to 1 mm. After this operation the granules were placed into a carrier fluid. Synthetic motor oil CASTROL W30 (BP, United Kingdom) was used as the carrier fluid. Motor oil and magnetic filler were weighed on the Unit G-200 (UNIT, China) scales with an accuracy of ± 5 mg. After this the filler was introduced into the motor oil and mixed thoroughly. As a result, the liquid phase – motor oil was 20 %, and the solid phase – nanomodified composite – 80%.

The hollow container with the form of a parallelepiped was loaded with magnetically controlled TM. The container from one plane contained neodymium magnet (1000 mT) (NPO Magneton, Russia). Neodymium magnet was made in the form of a cylinder with 50 mm diameter and 10 mm height. The counter plane contained an electric heater. The heating temperature reached to 70 °C.

FLUKE Ti9 thermal imager with 160 x 120 emission receiver, matrix in the focal plane and measurement range of - 20 °C to + 250 °C with an accuracy of ± 0.5 °C was used for contactless measurement of temperature field in the TM.

3. Results of experimental studies and analysis
Figure 1 shows the distribution of the temperature field in the TM taking into account the effect of the magnetic field over time of 45 sec and heating up to 70 °C (thermomagnetic convection).

![3-D thermogram of magnetically controlled TM](image-url)
Figure 2 shows the thermogram of magnetically controlled TM in the mode of thermomagnetic convection.

![Thermogram](image)

**Figure 2.** Thermogram of magnetically controlled TM (thermal accumulating material).

As the magnetically controlled TM is heated the magnetic properties change; and the cooler layer displaces the hot layer. Thus, thermoregulation on the heater surface and interaction with the environment is achieved. Since the developed TM can provide thermoregulation due to the effect of thermomagnetic convection and intensification of heat transfer does not require additional energy, this approach is economically expedient and technologically adapted for aerospace engineering.

4. **Methods for obtaining analytical functions for the thermoregulation system**

The efficiency of the thermoregulation system with TA (thermal accumulators) is related to the efficiency of optimizing the constructive parameters of the heater. It is possible to achieve this through mathematical modeling based on finite integral transform method.

The main question of mathematical modeling is the distribution of the temperature field of TA in the regime of thermomagnetic convection in various spatial volumes.

Modeling of TA is carried out taking into account that its form can be represented by unlimited multilayered plate, unlimited continuous and hollow multilayered cylinder, solid and hollow multilayered ball [9] Figure 3.
Figure 3. Multilayered bodies of canonical form: unlimited plate, ball, unlimited cylinder.

Consider mathematical model of TA with random initial conditions, inhomogeneous boundary conditions and distributed internal heat source.

\[
\frac{\partial t_i(r_i, \tau)}{\partial \tau} = \alpha_i^2 \left( \frac{\partial^2 t_i(r_i, \tau)}{\partial r_i^2} + A_{k,i} \frac{\partial t_i(r_i, \tau)}{\partial r_i} \right) + Q_i(r_i, \tau);
\]

\(i = 1, 2, ..., N; \quad R_{i-1} \leq r_i \leq R_i; \quad k = 0, 1, 2; \quad \tau > 0;\)

\(t_i(r_i, 0) = f_i(r_i);\)

\(\lambda_1 \frac{\partial t_1(R_0, \tau)}{\partial r_1} + \alpha_1 \left( t_1(R_0, \tau) - t_{c1}(\tau) \right) = 0; \quad \alpha_1 < 0;\)

\(\lambda_N \frac{\partial t_N(R_N, \tau)}{\partial r_N} + \alpha_N \left( t_N(R_N, \tau) - t_{cN}(\tau) \right) = 0.\)

\(t_j(R_j, \tau) = t_{j+1}(R_j, \tau); \quad \lambda_j \frac{\partial t_j(R_j, \tau)}{\partial r_j} = \lambda_{j+1} \frac{\partial t_{j+1}(R_j, \tau)}{\partial r_{j+1}},\)

\(j = 1, 2, ..., N-1.\)

Here:

\(r – \) space coordinate;

\(\tau – \) time;

\(N – \) number of layers in a multilayered area;

\(t_i(r_i, \tau) – \) temperature field of the i-area;

\(Q_i(r_i, \tau) – \) function of the internal heat source of the i-area;

\(\lambda_i, \alpha_i^2 – \) coefficients of thermal conductivity and thermal diffusivity of the i-area, respectively;

\(A_{k,i} – \) the equation coefficients determined by the type of coordinates:

– for a Cartesian coordinate system \(k = 0, A_{0,i} = 0;\)

– for a cylindrical coordinate system \(k = 1, A_{1,i} = r_i;\)

– for a spherical coordinate system \(k = 2, A_{2,i} = 2/r_i;\)

\(\alpha_i, \alpha_N – \) coefficients of convective heat transfer from external surfaces to the environment;

\(t_{c1}(\tau), t_{cN}(\tau) – \) environment temperatures as the functions of time;
\( R_{i+1}, R_i \) – coordinates of the i-area boundaries.

To exclude the coordinate \( r \), along which the body properties change stepwise, the formula for the transition to images is used:

\[
U(\mu, \tau) = \sum_{m=1}^{N} \frac{\lambda_m}{a_m^2} \int_0^{R_m} \rho(z_m) r_m^2 W_m(z_m, \mu) dz_m,
\]

(6)

where \( \rho(z) \) – is a weight function that is a solution of equation

\[
\frac{d^2 \rho(z_m)}{dz_m^2} - A_{k,m} \rho(z_m) = 0.
\]

(7)

The kernel of the integral transformation \( W_m(z_m, \mu) \) is a solution of the Sturm-Liouville problem with the corresponding homogeneous boundary conditions, determined to within constant factor (here parameter):

\[
\frac{d^2 W_m(r, \mu)}{dr^2} + \frac{A_k}{a_m^2} \frac{d W_m(r, \mu)}{dr} + \frac{\mu^2}{a_m^2} W_m(r, \mu) = 0;
\]

(8)

\( m = 1, 2, ..., N \), \( R_{m-1} \leq r \leq R_m \);

\[
\lambda_1 \frac{d W_1(R_0, \mu)}{d r_1} + \alpha_1 W_1(R_0, \mu) = 0;
\]

(9)

\[
\lambda_N \frac{d W_N(R_N, \mu)}{d r_N} + \alpha_N W_N(R_N, \mu) = 0;
\]

(10)

\[
W_j(R_j, \mu) = W_{j+1}(R_j, \mu); \quad \lambda_j \frac{d W_j(R_j, \mu)}{d r_j} = \lambda_{j+1} \frac{d W_{j+1}(R_j, \mu)}{d r_{j+1}}.
\]

(11)

\( j = 1, 2, ..., N - 1 \).

The solution of equation (8) has the form:

\[
W_m(r, \mu) = C_1 m \ Exp \left( -\frac{r}{2} \left( A_{k,m} + \sqrt{A_{k,m}^2 - 4 \frac{\mu^2}{a_m^2}} \right) \right) +
\]

\[
+ C_2 m \ Exp \left( -\frac{r}{2} \left( A_{k,m} - \sqrt{A_{k,m}^2 - 4 \frac{\mu^2}{a_m^2}} \right) \right).
\]

(12)

In the Cartesian coordinate system

\[
W_m(r, \mu) = C_1 m \ Sin \left( \frac{\mu}{a_m} r_m \right) + C_2 m \ Cos \left( \frac{\mu}{a_m} r_m \right).
\]

(13)

In the cylindrical coordinate system

\[
W_m(r, \mu) = C_1 m J_0 \left( \frac{\mu}{a_m} r_m \right) + C_2 m Y_0 \left( \frac{\mu}{a_m} r_m \right).
\]

(14)

where \( J_0(z), Y_0(z) \) – Bessel functions of the first kind, zero and first order, respectively.
5. Conclusion
There were investigated the mechanisms of thermomagnetic convection in the thermal accumulating material based on the synthetic oil containing ferromagnetic particles (nickel-zinc ferrite), paraffin and MWCNTs under the influence of magnetic field created by neodymium magnet with magnetic induction of 1000 mT. It was found that during the heating of the magnetically controlled TA the magnetic properties change; and the cooler layer displaces the hot layer.

The mathematical modeling of TA is carried out taking into account the fact that its shape can be represented by unlimited multilayer plate, unlimited continuous and hollow multilayer cylinders, solid and hollow multilayer balls. Analytical equations are obtained for determining the temperature field in the volumes containing TA.

The developed magnetically controlled thermal accumulator can provide thermoregulation due to the effect of thermomagnetic convection and intensification of heat transfer does not require additional energy. Such approach is economically expedient and technologically adapted for aerospace engineering.

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