Development of polymer composite materials and structures with their subsequent utilization after the mission

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Abstract. The article considers the transfer of utilization technologies for detachable elements of the launch vehicle (LV) structures during the launch at the powered phase after their detachment at the unpowered phase of the descent trajectory to the utilization of tanks for fuel and lubrication materials (FLM) delivered to outlying regions of the Arctic. Opposed to detachable LV structures, utilization of FLM tanks is carried out under ground conditions by burning fuel elements prepared from FLM tank structures in conventional boilers and domestic heating furnaces. The research task has been set considering the possibility of implementing the requirements in the design and construction of polymeric composite material (PCM) to manufacture combustible tanks for the FLM storage. The requirements have been formulated for the production stages of combustible PCM and utilization system including the definition of design and construction parameters of PCM. The results of preliminary experimental studies in terms of determining the combustibility of the proposed PCM and their strength characteristics have shown the possibility of developing combustible structures.

1. Introduction

Several factors negatively affecting the environment have been identified during the rocket-space activity. These factors include not only the LV launch process for spacecraft launch ascent but also the process of testing and manufacturing the LV elements in the shops of manufacturing plants, utilization of structures both during their manufacture and testing, as well as in the impact zones after the LV launches, utilization of rocket armament samples after de-alerting, etc. In this work the issues of reducing the environmental effect on the impact areas of the separating LV parts, as well as the transfer of the developed scientific-methodological approach to some systems of weapons, military and special equipment, and further to technical systems.

The accumulation of a significant number of metallic and rusting tanks with FLM residuals (from 3 - 5% of the initial capacity and more) is a negative factor for the environment: the destruction of containers, and chemical and mechanical contamination of the soil. Removal of the tanks to the mainland, for example, from outlying regions such as the Arctic, Chukotka, Eastern Siberia, etc., is an economically costly task, so they are usually left at the operating organization location, i.e. the relevant military unit. A common problem in the LV and FLM containers operation after the missions is the need to allocate significant areas where these containers are dispersed. The need to bring the allocated territories to their original state and environmental remedial action result in significant economic costs; therefore, this factor must be considered in the design of technical systems.

As shown by the research on the utilization of various structural elements made of metal and PCM in general, the existing methods of utilization can be presented in the form of two approaches:
- extraction of different materials from spent structures in land-based facilities for their subsequent use in the production of new products [1 - 4],
- reduction of a spent structure to a form that may be utilized by combustion to obtain thermal energy [5 - 8].

Both approaches have one common disadvantage. At the initial manufacture of the material, such as the PCM, from which the subsequently utilized structure is made, the subsequent utilization step was not considered as well as the possible energy recovery contained in that PCM.

In approach (2), one faces the problems of combustion products toxicity, both in the gas form and condensed products, slag.

A scientific-methodological approach has been devised [5 - 9] and applied to the tasks of advanced technical systems development considering the reduction of technogenic environmental impact during operation and utilization due to their combustion after the mission. Its main provisions can be formulated as follows:

- when developing advanced technical systems, it is necessary to make allowances for the utilization stage of structural elements, considering the reduction of technogenic environmental impact during operation and utilization, and possibility of material (energy) recovery; (3)
- the use of PCM in the constructions of the prospective technical systems results in the necessity to consider the separate stages of PCM design and construction; (4)
- the developed composition of PCM, which may include the energy material in the form of a filler, must not lead to the possibility of an explosion in the manufacture of both granulated PCM (raw materials), and in the manufacture of the combustible FLM containers from granulated PCM. (5)

Analysis of the literature [10 - 14] shows that the most promising matrices for problem solution are:

- polytetrafluoroethylene (PTFE);
- ultra-high molecular weight polyethylene (UHMW PE);
- polypropylene (PP);
- acrylonitrile styrene acrylate (ASA);
- polycarbonate (PC);

and their mixtures.

The filler in the developed PCM must solve the following tasks:
- providing thermal conductivity;
- ensuring electrical conductivity;
- mechanical strengthening;
- regulation of the composite material combustibility.

When developing the composite material composition, the following fillers will be considered:
- aluminum, aluminum oxide;
- carbon black;
- fibrous fillers (chopped glass fiber, carbon fiber, cotton fiber) and nanofillers (carbon nanotubes, graphene);
- wood flour, magnesium oxide, potassium nitrate.

2. Problem statement

In accordance with provisions (3), it is necessary to carry out theoretical and experimental research into the possibility of implementing the requirements in the design and construction of PCM to manufacture combustible tanks for the FLM storage, meeting the following set of requirements at all operation stages including disposal:

- combustibility and fire and explosion safety;
- thermal strength and electrical conductivity;
- environmental friendliness and calorific value. (6)
In accordance with provision (4), it is necessary to consider the development of a system for carrying out the utilization of the created combustible FLM structures based on the shredding of containers till the finely dispersed state and the subsequent manufacture of fuel elements.

In accordance with provision (5), the issues of fire and explosion safety should be investigated in the production of both granulated PCM and the combustible FLM containers.

At the considered research stage, problem (3) from the full list of problems (3)-(5) is studied.

3. Formation of requirements to the combustible PCM creation stages and recycling system

When creating combustible PCM, by analogy with the creation of complex technical systems, it is offered to introduce stages of design and construction. The PCM design stage includes determination of general parameters of PCM (matrices and fillers, meeting the list of requirements, i.e. boundary conditions according to (6), as well as availability of raw material base, etc.

The design stage involves determining quantitative characteristics of the parameters included in the created PCM. At this stage, the weight fractions of substances comprising matrices and fillers are determined and their optimization is carried out on the basis of the criteria:

\[ \max Q, \min L, \]

where \( Q \) is the calorific value of the resulting fuel cells, \( L \) is the mass of toxic substances in gaseous and condensed products.

Physical and mathematical models describing possible matrices and multicomponent fillers at the stages of design and construction of combustible PCM represent different dependencies; for example, at the design stage, it is a set of possible matrices \([M]_i\) and fillers \([N]_i\):

\[ ([M], [N], i = 1, 2...,] \]

with the following boundary conditions for the introduced parameters (6).

For the design stage, the physical and mathematical model of the PCM is considered as a sum of the matrix:

\[ M_i = \sum \alpha_{ij} m_j, \]

where \( \alpha_{ij} \) is the weight characteristics of the substances included in the \( m_j \) – matrix and fillers:

\[ N_i = \sum \beta_{ik} n_k, \]

where \( \beta_{ik} \) is the weight characteristics of the substances included in the \( n_k \) – filler.

As indicated above, the task of the design stage is to select \( \beta_i \) from the optimization condition of criteria (7) on the basis of experimental studies.

4. Results and discussion

In the present work, following fibrous and finely dispersed PCM are considered as promising materials for LV structures and FLM containers: organic plastic and PTFE.

PTFE has been chosen as a PCM matrix since it starts to decompose with gas release at heating to more than 400°C, and at more than 650-700°C it decomposes to monomers with the formation of a finely dispersed powder. The filler in the form of aluminum powder increases the thermal conductivity of the composite and is an energy component. The addition of the chopped carbon fiber to the PCM improves the strength properties of the composite material.

The combustion products of PTFE-based PCM have a finely dispersed structure and consist of chopped carbon fibers, PTFE monomers, and granules of aluminum trifluoride (with average size of 30-40 microns). It is confirmed by elemental analysis with the X-ray spectral method using an electronic microscope JEOL-5700 (Figure 1).
Due to high hardness and high packing density of PCM macromolecules based on organic plastic, para-aramid fibers are thermostable at elevated temperatures up to 220°C and resistant to cyclic thermal influence. Also, finely dispersed aluminum powder is added to the epoxy binder as a filler to increase thermal conductivity. Analysis of literature data and conducted experiments showed the most acceptable composition of PCM:

- aramid fabric “SVM” 54 - 56 %;
- epoxy binder ED-20 41 - 43 %;
- aluminum powder 2.7 - 3 % with dispersibility from 20 to 80 microns.

Table 1 presents the results of a comparative analysis of strength characteristics of the described PCM.

| Materials                  | $E$, GPa | $\sigma_{\text{max}}$, MPa | $\varepsilon_{\text{max}}$, % |
|---------------------------|---------|---------------------------|------------------------------|
|                           | OP      | CFRP                      | PTFE                         | OP    | CFRP                      | PTFE                         | OP    | CFRP                      | PTFE                         |
| $T$, °C                    | 20±2    | 37                        | 56                           | 0.2/6 | 654                       | 682                          | 13    | 1.7                       | 1.1                          | 160                           |
| 170±2                     | 23      | 41                        | 0.1/9                        | 421   | 516                       | 4.1                          | 1.8   | 1.0                       | 155                          |

* OP - Organoplastic based on aramid fabric “SVM” and epoxy binder ED-20, aluminum powder - 2.5%; CFRP - Carbon plastic from unidirectional tape LU-P/0.1 and epoxy binder ENFB

According to the test results, the organic plastic based on “SVM” fabric and modified epoxy binder with aluminum powder has a level of physical and mechanical characteristics comparable to carbon plastic based on carbon fabric. PTEE-based PCM is, on the contrary, considerably inferior to fibrous PCM and is a weak competitor for application in power elements of the LV construction, but it can be used in non-power constructions and for the FLM containers.

To carry out a comparative analysis of the presented PCM combustibility, the following samples were formed: sample No. 1. PTFE – 75%, aluminum powder – 15%, carbon black N330 – 10%; sample №2. PTFE – 88%, aluminum powder – 10%, multiwalled carbon nanotubes production – 2%; sample №3. PTFE – 88%, aluminum powder – 10%, chopped 0.1 mm carbon fiber – 2%; sample №4. PTFE – 85%, aluminum powder – 10%, multi-wall carbon nanotubes – 2%; chopped carbon fiber (0.1 mm) – 2%, potassium nitrate – 1%; sample №5. PTFE – 86%, aluminum powder – 10%, multi-wall carbon nanotubes – 2%; chopped carbon fiber (0.1 mm) – 2%; sample №6. The organic plastic based on aramid fabric “SVM” and epoxy binder ED-20, aluminum powder – 2.5%.

For comparison, PCM samples used in traditional designs of detachable LV parts were used: sample No. 7. Carbon fiber-reinforced plastic made of unidirectional tape LU-P/0.1 and epoxy binder ENFB; sample No.8. The organic plastic made of “SVM” fabric and EDT-10 epoxy binder; sample
No. 9. Carbon fiber-reinforced plastic made of Panex 35 unidirectional carbon harness and epoxy-vinyl ether binder.

Figure 2 provides the results of the experimental studies on heating samples for samples 1 - 8, as well as the results of the thermogravimetric analysis for sample 9. The results are shown as the graphs of weight changes as a function of the heating temperature.

![Graph of changes in the material samples mass depending on the heating temperature and a possible ideal region of PCM parameters designed for combustible detachable LV structures](image)

Figure 2. Graph of changes in the material samples mass depending on the heating temperature and a possible ideal region of PCM parameters designed for combustible detachable LV structures

The combustibility of PCM on organic plastic, as follows from the results shown in Figure 2, requires significantly less heat compared to the carbon fiber reinforced plastics used in standard LV structures. The combustibility of PTFE-based PCM shows a dependence similar to that of organic plastic on the maximum heating temperature for the active phase of mass loss but has a sharper character of mass loss starting at 500°C. As a result of experiments, it is revealed that independent combustion and destruction does not continue for any of the investigated samples without heat supply from heating elements of the stand after reaching the temperature of active mass loss start.

5. Conclusion

1. It was shown that the utilization technologies for the detachable elements of LV structures based on combustion of structures can be transferred to the utilization of FLM tanks, delivered to outlying regions of the Arctic.

2. The main provisions were formulated for the developed scientific-methodological approach to the development of advanced technical systems, with due account of the reduced technogenic environmental impact during operation and utilization.

3. The research tasks were stated considering the possibility of implementing the requirements in the PCM design and construction to the manufacture of combustible containers for the FLM storage.

4. The requirements were formulated for combustible PCM creation stages and utilization system, including the definition of design and construction parameters of PCM (matrices and fillers, meeting the list of requirements, i.e. boundary conditions, composition, as well as availability of raw material base).

5. Results of the conducted preliminary experimental studies devoted to the definition of the offered PCM combustibility and its strength characteristics showed the possibility of the development of combustible constructions.
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