Analyzing fundamental problem of designing incinerated payload fairings made from composite polymer materials

Yu Iordan
Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

Abstract The article considers fundamental engineering problem of designing the payload fairing (PLF) for a launch vehicle (LV) made from polymer composite material (PCM) with high temperature resistance and minimum mass, with the PLF being incinerated after separation from the launch vehicle on the atmospheric section of the descent path. The energetic material (EM) is introduced into the PCM, which provides heating of the PCM structure to the ignition temperature and subsequent PLF combustion under the conditions of the incoming air flow. A comparative analysis of the problems arising at different life cycle stages in creating and operating traditional (PLFT) and incinerated (PLFI) payload fairings is carried out. Example options for energetic materials and possible designs of the individual PLFI elements are given.

1. Introduction
The environmental effect of launch vehicles (LV) in the impact zones of spent stages boosters (SS) is one of the main problematic issues in the LV operation. It should be noted that for each launch path, the largest area is formed by the impact zones of payload fairing (PLF), interstages and aft-interstages. So, for the "Soyuz" type LV, the total area of impact zones for exhaust boosters (side blocks and central block) is ~ 35% and impact zones for PLF and AIS are ~ 65 %; for “Zenit” LV, impact zones area for the 1st stage booster is ~ 19 – 20% and the impact zones for PLF are ~ 80 - 81 %; the “proton-M” LV impact zones area for the 1st stage booster is ~ 28 %, and for PLF it is ~ 23 % (if special impact zone is allocated), the impact zones area for the 2st stage booster is ~ 49 % [1, 2]. After each LV launch in the impact zones, work is carried out to find the separated stages, the payload fairing, to cut and remove them to storage sites, with subsequent recycling, etc. Besides damage to the environment and economic activity of local business, this results in additional social tension.

Currently, the problems associated with the entry of space objects into the atmosphere with hypersonic speeds and degradation of these object structure materials are thoroughly considered [3]. There are known technical solutions providing almost complete absence of impact zones for the spent stages [4]. For the most part, such studies relate to the SS, while "dry" compartments, such as PLF halves, separate at such motion parameters that heating does not reach sufficient temperatures to ensure their combustion process in the dense layers of the atmosphere [5].

In works [6, 7] a method is proposed as one of the possible solutions to reduce the impact zones. This method is based on the introduction of an energetic material (EM) into the existing PLF structure. The material, when burned, will heat the PLF structure material to the ignition temperature when moving along the atmospheric section of the descent path. These studies have shown the possibility of the PLF destruction, however, to bring the structure to a finely dispersed state requires a significant increase in the EM mass and, accordingly, all PLF because of the currently used PCM.
Modern PLF represent a two-leafed three-layer structure (figure 1), the outer layers of which are made from PCM based on carbon fibers and aluminum honeycomb filler [8]. The widespread use of PCM in rocket and space technology products is due to the possibility to create structures with a number of unique mechanical and physical properties, such as high heat resistance, low coefficient of friction and thermal expansion, high resistance to atmospheric influences and chemical reagents, etc. [9], which hinders the implementation of the proposed method of the PLF combustion.

**Figure 1.** Payload fairing of the launch vehicle: a) assembled PLF without thermal protection; b) PLF element: 1, 3-outer layers based on carbon fibers, 2-aluminum honeycomb filler.

Based on the above said, it is proposed to replace the currently used PCM, honeycomb core with the materials and structures capable of providing the traditional requirements for operation on all life cycle stages of the launch vehicle (manufacturing, storage, operation on the launch and technical complexes, on the active sector of the ascent trajectory) [10].

When an incinerated payload fairing (PLF₁) is designed, fundamental problems arise in the field of engineering, in particular: a) when creating a PCM with new thermal, physical and chemical properties; b) the choice of possible energetic materials that are part of the PCM; c) the choice of PCM structures providing durability, the ability to provide combustion conditions, etc.

### 2. Problem statement

Based on the analysis of the problem state for the design and construction of the incinerated PLF₁ structures, the problem statement is formulated as follows: to determine requirements to design parameters of the PLF₁ made from PCM with introduced EM, providing the required thermal power characteristics of the PLF₁ in the boost phase of the LV launch with further combustion on the atmospheric part of the ascent trajectory after separation from the LV.

Solutions to the formulated problem of the PLF₁ design and construction are proposed as based on the existing scientific and methodological framework for designing traditional PLF from PCM [11] and provide for the solution of the following task sequence:

- comparative analysis of the PLF₁ and PLF₁ operation stages;
- comparative analysis of the PLF₁ and PLF₁ design parameters;
- comparative analysis of the PLF₁ and PLF₁ design stages.

Illustrated by selecting the filler structure for the PLF₁, the replacement of aluminum honeycomb filler with the filler made as a corrugated structure from EM is to be considered.
3. Theoretical studies

The purpose of the PLF is to protect the payload from the incoming air flow, radiation, temperature changes, from mechanical effects on the atmospheric section of the LV ascent trajectory during the passage through dense layers of the atmosphere.

On the active part of the ascent trajectory, PLF_T and PLF_I should provide the same operational conditions. Moreover the PLF_T after fulfilling its mission and separation from the LV moves in free-air conditions, and its life cycle ends with the landing in a predetermined impact zone, where it is evacuated and then disposed of. The PLF_I recycling stage is carried out on the atmospheric section of the descent trajectory and requires no impact zones, as well as the expenditures for searching, removal and subsequent recycling.

Table 1 shows the compared positions of PLF_T and PLF_I at the PLF operation stages on the active and passive parts of the trajectory.

Table 1. Comparative analysis of the payload fairing operation stages.

| № | Positions (criteria) to choose PLF design parameters | Traditional PLF_T | Incinerated PLF_I |
|---|-----------------------------------------------|-----------------|-----------------|
| 1 | The active part of the trajectory | | |
| 1.1 | Thermal power loading | + | + |
| 2 | The passive part of the trajectory | | |
| 2.1 | Unguided flight: | | |
| | - in a vacuum | Combustion process | | |
| | - atmospheric section of the descent path | Unguided flight | Combustion of the shell from carbon fiber |
| 2.2 | The impact zones | Up to 80% of the SS impact zone | – |
| 2.3 | Elimination of launch consequences | Search, cutting, removal, recycling | – |

The following main conclusions can be drawn from table 1:

– the fundamental difference between PLF_T and PLF_I is the absence of impact zones, whose area are several times larger those of impact zones for spent LV first stages;

– an additional operation stage is introduced for the PLF_I compared to the PLF_T, where the combustion process is carried out;

– one of the PLF_I design objectives is the choice of the descent trajectory interval, on which the combustion occurs.

Table 2 presents a comparative analysis of the PLF_T and PLF_I design parameters based on the set design parameters in [11].

Table 2. Comparative analysis of design parameters.

| № | Design parameters of PLF | Traditional PLF_T | Incinerated PLF_I |
|---|--------------------------|-----------------|-----------------|
| 1 | Structure and reinforcement scheme of the outer base layer | It is selected due to the thermal power loading | It is selected due to the thermal power loading + the condition of combustion on the atmospheric section of the descent path |
| 2 | Structure and reinforcement scheme of the inner base layer | The filler design is determined from the condition of ensuring the | The filler structure is determined from the strength conditions + the condition of combustion on the |
| 3 | Constructive filler parameters (height, size) | | |
 bearing capacity of the structure | atmospheric section of the descent path
---|---
4 | The thickness of the heat-shielding coatings | It is determined from the conditions of structure thermal loading | It is determined from the conditions of structure thermal loading + the condition of combustion on the atmospheric section of the descent trajectory
5 | The parameters of the ribs cross-section | It is determined from the conditions of PLF power loading | At the initial stage, it is assumed to be identical to the regular PLF

The following main conclusions can be drawn from the results given in table 2:
– the list and the number of the PLF and PLF design parameters for the design stage under consideration are assumed as the same;
– for PLF, the movement along the descent path does not affect the choice of design parameters, and the life cycle ends with recycling after falling to the ground;
– the PLF recycling stage sets new requirements to the design parameters and involves ensuring the PLF structure combustion conditions on the atmospheric part of the descent trajectory;
– the coordinates of the vector for design parameters of the traditional PLF $X_T(x_1, x_2, x_3, x_4, x_5)$ differ significantly from the coordinates of the vector for design parameters of the incinerated PLF $X_I(x_1, x_2, x_3, x_4, x_5)$ due to the additional requirements caused by the changes in the PLF operation stages.

Consider the main positions of the stages to solve the PLF design problem. Table 3 presents a comparative analysis of the PLF and PLF design stages.

Table 3. Comparative analysis of the stages to solve the payload fairing design problem.

| № | Stages to solve the problem | Stage content for PLF | Stage content for PLF |
|---|---|---|---|
| 1 | Determination of the aerodynamic heat flow and the maximum temperature for the PLF structure | + | + |
| 2 | Analysis of applied heat-shielding coatings | + | + |
| 3 | Determination of optimal PLF design parameters | Determination of each structural element thickness | Determination of the structure and reinforcement scheme for base layers and filler structure |
| 4 | Verification calculations of the optimal PLF structure variant | Selection of rational parameters for the honeycomb filler cell | The choice of rational parameters for load-bearing layers and filler, based on the selected energetic material |

Analysis of the results in table 3 shows that, unlike PLF, the following additional stages are introduced:
(a) analysis of energetic materials and structures;
(b) determination of the structure and reinforcement scheme of the base layers and the filler structure.
Evaluating the replacement of design and filler material

Using the choice of the filler structure as an example, a consideration should be made of the honeycomb aluminum filler replacement with the filler made as a corrugated structure, according to the method [12]. The new filler must:

a) provide similar strength, operational, and technological characteristics;
b) allocate a sufficient amount of heat during the combustion to heat the carbon-fiber material to the ignition temperature.

It is proposed to consider PCM based on ABS structure [13] with the EM introduction as one of the possible materials. The filler is proposed to be made in the form of a corrugation, and the corresponding parameters are to be determined from the strength endurance condition (condition a). When the chosen filler structure burns, the necessary quantity of heat (condition b) shall release. If this condition is not met, the filler mass should be increased in accordance with the proposed method [15].

Figure 2 shows the design diagram to the filler structure parameters on the example of cellular construction and corrugations.

![Figure 2](image)

Figure 2. Computational scheme to estimate the filler parameters: a) honeycomb filler; b) corrugation filler

The results of the evaluating calculations for the filler design parameters from the strength endurance conditions (condition a) and the required heat amount release condition (condition b) are presented in Table 4.

| Material | Embodiment | The edge width, \(a_c\), mm | Wall thickness, \(\delta\), mm | Density, \(\rho_0\), kg/m\(^3\) | Width, \(h_3\), mm | Specific gravity, \(m_3\), kg | Heat, Q, kJ |
|----------|------------|-----------------------------|-----------------------------|-----------------|----------------|----------------------------|-------------|
| aluminum | honeycomb  | 0.020                       | 33.018                      | 33              | 1.09          | –                         | –           |
| ABS      | honeycomb  | 0.075                       | 87.318                      | 13              | 1.14          | 9.209                     |             |
|          | corrugation| 0.060                       | 57.960                      | 19              | 1.10          | 8.886                     |             |

As follows from the results given in Table 4, there is a fundamental possibility to choose the design and material of the filler providing both strength conditions and the release of the required heat amount.

4. Experimental studies results

As a possible example, the filler structure in the form of an aluminum honeycomb with the parameters given in Table 4 and the energetic material in the form of a mechanically activated pyrotechnic composition \(B_4C + Ti\), as well as with other energetic compositions [6, 14], was considered. Figure 3 shows the result of the maximum structural element destruction.
Experiments with pyrotechnic compositions showed the possibility of the structural element dispersion, however, it was not possible to achieve a complete mass loss for a number of reasons:

- aluminum honeycomb filler is not combustible, because aluminum burning is possible only in finely dispersed form;
- combustion of pyrotechnic composition is accompanied by gas formation, which leads to, besides heat loss, an increased pressure in the filler layer;
- combustion of mechanically activated pyrotechnic composition provides a gas-free combustion mode, but during the chemical reaction, the combustion products evolve into the condensed phase;
- the introduction of pyrotechnic composition in an amount sufficient for burning the structure leads to an additional increase in the PLF mass.

5. Discussion
The experiments have shown the feasibility of changing not only the structure and the filler material, but also the structure and material of carbon fiber, in particular, the EM introduction in its composition.

A comparative analysis of PLF_T and PLF_I showed that the main difference lies at the PLF operation stage after its mission being fulfilled, namely the PLF_I combustion in the atmospheric section of the descent trajectory. To ensure the combustion of the payload fairing structure, additional stages are introduced when solving the problem of PLF_I design. Based on the combustion conditions, new requirements to the PLF_I design parameters are formed.

As an example, the replacement of a honeycomb aluminum filler with a similar and corrugated filler made from another material was considered. Possible variants of the filler structure are shown in figure 4.
6. Conclusion

1. One of the directions to solve the problem of reducing the man-made effect of rocket and space activities on the environment, based on decreasing the impact zone area allocated for the LV payload fairing halves is considered.

2. Appropriate scientific and methodological approaches for traditional PLF design from PCM are taken as a basic method to select design parameters and a list of design and structural parameters.

3. Additional design steps have been introduced into the life cycle for a incinerated PLFI.

4. An example is given that shows the possibility to develop individual elements of the PLF1 structure (the filler material and structure).

5. The limited possibility of the PLF structure combustion caused by the choice of the material and the filler structure is shown.

Acknowledgments

The research was supported by the RSF grant for the project "Development of scientific-technical fundamentals of the combustion of the separated elements of space rockets with the goal of reducing the acreage of the impact areas" the Agreement No. 16-19-10091.

The author thanks the scientific supervisor, doctor of technical Sciences, Professor Trushlyakov Valery Ivanovich.

References

[1] Shatrov Ya 2010 Ensuring the environmental safety of rocket and space activities (Moscow: Tsniiimash) p 261

[2] Avdoshkin V, Averkiev N, Ardashov A and others 2016 Problem questions of use of routes of launches of spacecrafts and areas of falling of separating parts of rockets of space appointment (SPb: ASA named after A Mozhaisky) p 372

[3] Shoemaker M, van der Ha J, Abe S and Fujita K 2013 Trajectory Estimation of the Hayabusa Spacecraft during Atmospheric Disintegration Journal of Spacecraft and Rockets vol 50 pp 326-336

[4] Falcon 9 attempts ocean platform landing. URL: www.spacex.com/news/2014/12/16/x-marks-spot-falcon-9-attempts-ocean-platform-landing (accessed: 20.02.2019)

[5] Fedorov A V 2012 Fundamentals of space rocket systems (SPb) p 243

[6] Monogarov K, Trushlyakov V, Zharikov K, Dron M, Iordan Y and Davydovich D 2018 Utilization of thermit energy for re-entry disruption of detachable rocket elements made of composite polymeric material Acta Astronautica vol 150 pp 49-55

[7] Trushlyakov V, Shatrov Ya, Lempert D, Iordan Yu and Zarko V 2016 Rocket payload fairing Patent Russia no 2581636

[8] 1991 Three-layer structures with carbon fiber cladding and aluminum honeycomb core, glued Russian Standard no 92515690

[9] Bulanov I M, Vorobei V V 1998 Technology of rocket and aerospace structures made of composite materials (Moscow: MSTU named after N Baumana) p 516

[10] Trushlyakov V I, Iordan Yu V, Davydovich D Yu, Zharikov K I, Lempert D B 2018 Development of proposals for the synthesis of polymer composite materials capable of combustion after the mission J. Phys.: Conf. Ser. 1134, 012061
[11] Kondratev A 2010 Design of the payload fairings of launch vehicles made of polymer composite materials with simultaneous thermal and power effects Design and manufacture of aircraft vol 4 p 11–22

[12] Panin V F 1991 Designs with filling (Moscow: Engineering) p 271

[13] Clark B, Zhang Zh, Christopher G and Pantoya M 2017 3D processing and characterization of acrylonitrile butadiene styrene (ABS) energetic thin films J Mater Sci pp 993-1003

[14] Zarko V, Lempert D, Iordan Yu and Trushlyakov V 2016 Preliminary assessment of the possibility of using mechanically activated pyrotechnic compositions for burning composite materials (Omsk) 2 pp 252 – 257

[15] Trushlyakov V, Zharikov K and Davydovich B 2019 Combustion possibility assessment for separating launch-vehicle components during atmospheric phase of descent trajectory Acta Astronautica https://doi.org/10.1016/j.actaastro.2019.02.003