Energetic Compositions Application for the Reduction of the Environmental Pollution Because of Space Vehicle Launches

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Article info

Abstract

Technogeneous impact of rocket and space activities on the environment is one of the most actual problems of practical cosmonautics. This technogeneous impact is not only the pollution of near Earth space with space debris (worked-off stages of space launch vehicle (SLV)), but also the pollution of significant areas on the Earth surface with worked-off lower stages of SLV, which fall down after having accomplished their mission. In OmSTU and IPCP RAS it was suggested to apply different self-burning compositions, generating hot gases for the evaporation of the unused residues of liquid propellant in tanks of SLV. Then the mixture of the evaporated compounds together with the gaseous combustion products from gas-generating compositions is used as propellant mixture for the autonomous gas rocket engine. Such a solution would decrease considerably the level of the environment pollution and additionally it increases the energetic characteristics of SLV. For example, in the case of the second stage of SLV «Soyuz-2.1.v» it increases the total velocity by 5%. Also it is proposed to use firing the pyrotechnic compositions like (thermites) for the fairings heating up to the temperature when the fairing material can be ignited in air. It would reduce considerably the amount and the mass of the separating parts of SLV that fall to the Earth.

1. Introduction

1.1. The main sources of environmental threat because of the rocket space activity

During a few first decades of the space exploration the designers of rocket-space technologies did not pay attention to the fate of the launching objects after they have accomplished their missions [1]. Only at the end of the XX century, when it became clear that the pollution because of the rocket-space activities has already reached the level when artificial space objects began to collide in space, it was decided to change the approach to the design of space launch vehicles (SLV) and space crafts (SC) for a considerable reduction of the environmental threat because of the rocket space activity.

As for technogeneous influence of rocket space activity on environmental pollution there are two main problems: a) the near Earth space and b) the areas of falling the separating parts of SLV launching to the operation orbits [2, 3].

As for the near Earth space pollution, the main problem is the increase of the amount of space debris (especially, long-measuring such as upper stages of launch vehicles and space crafts) after they have accomplished their missions [4, 5]. Years of SLV launching since the beginning of the space era have already led to a sad fact that in orbits up to 2000 km high (the orbit area of the near Earth space that is the most applying for SC moving) more than 800 worked-off stages of SLV have been accumulated, with total weight being more than 1200 t [6].

A significant portion of the space debris on these orbits are worked-off stages of SLVs, because the weight of SCs having ended their activity is considerably less than the SLVs weight. Moreover, the worked-off stages are potentially explosion dangerous because their fuel tanks contain still unused residues of liquid propellants.

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Recently many international organizations develop projects aimed at cleaning the most polluted orbits of the near-Earth space. The main directions of these researches are divided into two parts [7]:

1. Decrease in arrival of lunched space rocket objects into the protected areas of the near Earth space (orbits up to 2000 km altitude and the geostationary orbit of 36000 km high and zero inclination) because these objects transform to space debris after executing their mission.

2. These orbits cleaning from the SLVs and SCs, which were lunched earlier and have already ended their activity.

In the first direction for a new creating SLVs and SCs one has to develop acceptable on-board systems, able to transfer the worked-off SLVs and SCs (after they have ended the activity) to the orbits with the ballistic existence lifetime less than 25 years (for the orbits altitude up to 2000 km), or to the burial orbits (higher than 2000 km), where the ballistic lifetime is more than hundreds of years;

As for the second direction, an intensive development of various projects continues by practically all national space agencies [8–12].

1.2. New trends in the problem resolution

1.2.1. Decrease in arrival of worked-off SLVs into the protected areas of the near Earth space

A few years ago initially in the US, then in France and in Japan the descents of *worked-off* SLVs have been realized after the accomplishing their main missions. To realize this manoeuvre the energy contained in unused propellant residues was utilized [13–15]. Because of the propellants and the engine construction specifics (3% or so of the liquid components initially charged in tanks cannot be used completely) in Russia it was developing recently [16–18] another approach to energy extraction from the unused residues of liquid propellant. It was proposed to install additional devices containing self-burning energetic compositions (EC) like gun powders or solid composite propellants. In the specially defined instant of time the EC is ignited (an electric pulse is often enough) and burns with the formation large amount of hot (3000 K and even higher) gases. The hot gases fill the fuel tanks and gasify the liquid components residues. Then all the gasified compounds are sent to the specially designed gas rocket engine and the obtained thrust is used for further moving (there are different tasks). Different kinds of EC have

been considered, e.g. for kerosene gasification it is rather safe to use combustion products of many ECs (e.g. hot gun powder combustion products). As for liquid oxygen gasification it was proposed to use special ECs that do not contain gases able to be oxidized (hydrogen, carbon monoxide). One of examples of this kind of EC is the formulation $CaO_2 + Mg + NaClO_3$ (1:1:1 moles) forming only oxygen as the gaseous combustion product.

The calculations showed that for the gasification of the residues of liquid components in the second stage of SLV like «Soyuz-2.1» (total initial propellant mass is about 20 t, the mass of kerosene residue is 200 kg, and liquid oxygen mass residue is 410 kg) it is needed about 90 kg of EC. This method allows increasing the characteristic velocity of SLV by ca. 350 m/s that is by 6.7% or so.

Simultaneously with the development of the chemistry of EC able to gasify liquid propellants residues, new variants of SLV constructions, realization of on-board systems for worked-off SLVs re-entry, modes of SLVs re-entry, e.g. [19, 20] were proposed for solving the problem.

1.2.2. The reducing the anthropogenic impact because of SLVs lunching at areas fall

The second task to avoid environment ecological pollution because of rocket-space activity is the necessity to allocate huge territories for separated parts of SLVs and other elements of construction (fairings, interstage compartments) via re-entry them after they have finished their function [3]. After these objects leave the SLV one has necessarily to carry out a full range of activities in the Earth areas – the search numerous fragments, the defragmentation of man-made long-measuring objects, their transfer to storage spaces (using helicopters, trucks, etc.), their utilization and the soil recovery to its original state. Besides, economic agents are paid compensation for the economic benefits loss, it is needed to pay the environmental penalties, and the payment for the land use. All these costs are included into the total SC launch cost. The solution of this problem is especially important for such states as Russian Federation, People's Republic of China and Republic of Kazakhstan, because the fall areas are located primarily in their territories, while in other countries they are located primarily in the water areas.

There are proposals how to solve the task (e.g. for the lower stages of SLV «Falcon-9») in order to avoid the worked-off parts fall, e.g. by the con-

trolled descent with a soft landing on the given area [21]. But such a solution takes a considerable weighting of the construction, an increase in the cost of engineering efforts, etc. Anyway this way cannot reduce fall areas for the re-entry of such objects as fairings and interstage compartments. Fall areas for fairing leaves (FL) occupy up to 5000–8000 km². So, without solution of the task of fairing leaves re-entry the total problem to considerable diminution of the fall areas cannot be solved.

To solve the problem of reducing the fall areas for fairing leaves it was proposed an alternative solution – the use of pyrotechnic compositions (PC) like thermites. Thermites burn with the heat release of 2.0–5.0 MJ/kg, and none external oxidizer like air is needed. It is rather easy to ignite thermites. The essence of this proposal is based on the following considerations: during descending the FLs through dense atmosphere layers they are heated up to 200 °C or so, but it is not enough to triger the aluminium combustion in air (it is needed 500–600 °C). The additional heat release because of thermites combustion has to increase the temperature of aluminium in FLs and ignite aluminium in air. Different space objects burn in dense atmosphere layers in the course of re-entry [22–24]. It was showed that it is possible to heat aluminium objects at their reliable mechanical contact with PC like thermites [25–28].

The thermochemical analysis showed that if one of the most common PC (33.8% Al + 67.2% Fe_2O_3) is kept together with aluminium FL in mass ratio 1:10, the PC combustion increases the temperature of all system by ~350–450 °C [28].

The scope of the present study is to increase in number the choice of PCs in comparison with those described in [28] and also to consider the possibility of using certain metals with a low ignition temperature as the heat source.

2. Materials and methods

If one uses certain metals as a heat source, these metals may have the heat of combustion not so great as Al or Mg; the main requirement is a low ignition temperature. It means that if the FL's surface is covered with such metals (partially or fully) they would ignite in air at the temperature below the temperature of aluminium ignition. In this way their combustion would warm-up the FL material up to the temperature when this material ignites.

We should notice that the use of the heat of free metals and alloys combustion in air for FL materials warming-up has both advantages and disadvantages in comparison with the method of using PC combustion. On the one hand the metal combustion may take place only when the falling FL reaches the altitude with a certain air pressure while PC can burn at any external pressure. On the other hand the heat release due to the metal combustion in air is greater than the heat release at PC combustion without air, so it can allow one to achieve the goal with less FL weighting.

2.1. Assumptions and limitations, preliminary baseline data

Preliminary estimations allow setting the following parameter ranges for the PCs operation:
• at the altitude higher than 55 km from the Earth's surface;
• time of flight on the said PC altitude ranges up to 100 sec;
• the initial PC temperature is lower than 500 K (~220 C);
• PC's mass must be less than 7% of the FL mass.
• the heat transfer mechanism from the PC to the FL is instantaneous, with no loss to the environment, i.e. we do not count the heat inflows and outflows with the oncoming aerodynamic flow during all descent process. Thus, an adiabatic model of the process is under consideration but surely there is a certain amount of heat loss in the reality.

2.2. Methodology of the temperature growth estimation

The method of solution is as follows: an additional material that is installed on the FL surface and is kept in mechanic and thermal contact with the FL is initially the PC itself (usually thermite like Mg + Me_nO_m mixture), and finally after thermite burning out it turns to mixture MgO + Me. The calculations have been carried out using the TERRA code for high temperature equilibrium calculations [29]. This code contains all thermochemical data of all chemical products (including substances in different phase conditions) that may appear basing on all possible combinations of chemical elements in the PC mixture and in the mixture metal-initiator + material of FL + air.

As it was set preliminary, the combustion of PC or metal-initiator has been considered as the only energetic source for the whole system heating, the initial system for thermochemical calculations for

the case PC + aluminium FL did not contain additional oxygen (only the PC itself and aluminium). Besides, Al was set as an inert material (TERRA code allows doing that). In the case when the metal-initiator combustion in air was the source of aluminium heating, a free oxygen was included to the calculated mixture Al + metal-initiator in amount which is needed to oxidize the metal-initiator only, but not aluminium in FV.

The initial temperature was set being 293 K. Namely PCs (mainly, thermites) and some pure metals and alloys have been considered as the heat source, because they can be ignited at lower temperature that it is needed for aluminium ignition.

3. Results and discussions

Stoichiometric PC mixtures of Mg with the following oxides (PbO_2, CrO_3, BaO_2, MoO_3, CuO, SnO_2, MnO_2, ZnO, Sb_2O_5, Fe_2O_3, Sb_2O_4, SrO_2, Bi_2O_3) have been considered. Table 1 demonstrates in part (30–40%) the obtained results – the temperature growth ΔT of aluminium FL as the function of the PC nature and the PC content (% in the initial FL mass). Figure 1 illustrates this dependency more circumstantially.

It should be noticed that there is an explicit bend on some curves $\Delta T = f$ (PC percentage) when temperature runs into 660 °C or so. It is the consequence of the start of the aluminium melting, so the temperature remains the same until all aluminium melts. The most ΔT growth may be reached with the use of Mg stoichiometric compositions with CrO_3, MoO_3, MnO_2, Sb_2O_5 ($\Delta T = 500$ °C may be obtained at 7.5–11.0% PC), the least ones – with Bi_2O_3, BaO_2, SnO_2, PbO_2 ($\Delta T = 500$º may be reached at least at 16–24% PC). At current stage
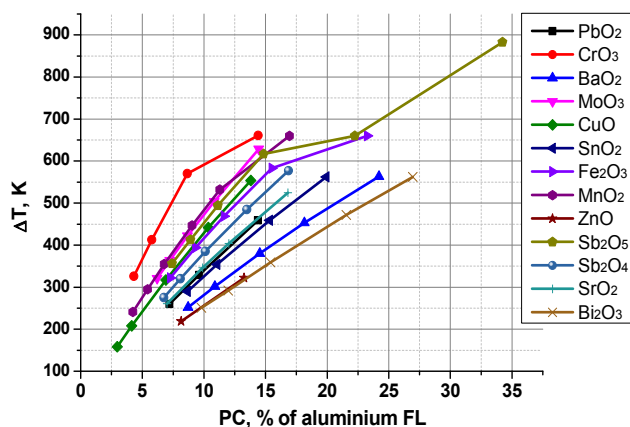
of the investigations it is too early to affirm that a PC with the higher energy potential would be better for the given task solution, because the ignition temperature T_{ign} is very important too. The last one does not depend on the energy potential, but on the facility of the oxygen atom divulsion from the metal oxide molecule and on the chemical properties of the metal in PC. For example, the thermites basing on BaO_2 or PbO_2 inflame more easily than PCs based on Fe_2O_3, though the heat release is greater in the case of Fe_2O_3.

If the combustion of some metal-initiators (Mg, Ce, La, Zr or alloys able to flame up in dense atmospheric layers instantly when the temperature reaches the certain value) is the only energetic source for aluminium heating, the current calculation shows that it allows to decrease the fraction of the "heater" in about two times as compared with the case when PCs (thermites) are used (Table 2, Fig. 2). It is evident that the application of La, Ce or the ferrocerium alloy as metals-initiators is considerably less effective energetically than the application of the same mass of Zr, moreover Mg. For example, for aluminium heating from 0 to 400 °C one has to install about 6% Ce or La while it is enough 2.6 and 1.5% Zr and Mg correspondingly to accomplish the same task. But anyway the combustion of the least energetic metals (Ce or La) among the metals under consideration generates the same ΔT growth as the most energetic PC based on thermites (Mg + CrO_3, compare data in Figs. 1 and 2). In this paper we considered the burning of aluminum FLs only. The firing of FLs made of carbon fiber would be much more difficult to arrange because the ignition temperature of carbon fiber is considerably higher than the ignition temperature of aluminum.
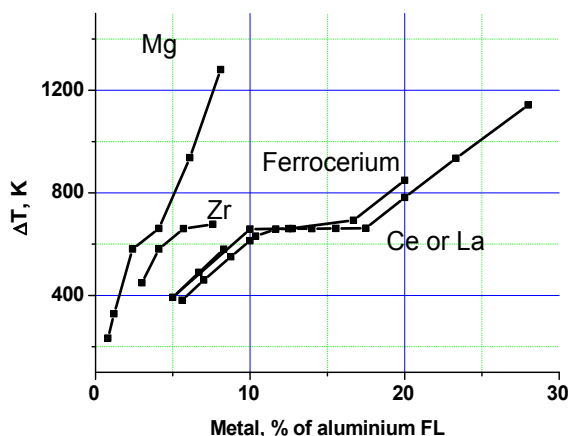

Fig. 1. FL temperature growth as the function of the PC content.

Fig. 2. Calculated temperature growth as the function of the metal-initiator percentage in aluminium FL.

Table 1
Calculated values ΔT at some thermites applying as PCs

Stoichiometric PC mixture	PC content in the initial FL mass, %	ΔT, °C	Stoichiometric PC mixture	PC content in the initial FL mass, %	ΔT, °C
$Mg+PbO_2$	7.2	260	$Mg+Bi_2O_3$	9.8	251
	14.4	459		26.9	562
$Mg+CrO_3$	4.3	326	$Mg+SrO_2$	7	261
	14.4	661		26.9	562
$Mg+BaO_2$	8.7	252	$Mg+Sb_2O_4$	6.7	275
	24.2	563		16.9	577
$Mg+MoO_3$	6.2	321	$Mg+Sb_2O_5$	7.4	356
	14.5	629		22.2	660
$Mg+CuO$	3	158	$Mg+ZnO$	8.2	219
	13.8	554		13.3	322
$Mg+SnO_2$	8.7	290	$Mg+MnO_2$	4.2	241
	19.9	562		6.8	355
$Mg+Fe_2O_3$	7.3	322		11.3	532
	23.3	660		16.9	660

Table 2
Calculated ΔT values when metals-initiators are used

Metal-initiator	Metal-initiator content in the initial FL, mass %	ΔT, °C
Mg	0.8	233
	2.4	581
	4	661
	8.1	1281
Zr	3	449
	4.1	581
	7.6	677
Ferrocerium alloy (5% Fe + 45%Ce + 25%La + 7% Nd + 8%Pr)	5	392
	6.7	490
	10	659
	16.7	693
Cerium or lantanum	5.6	381
	8.7	551
	10	613
	12.7	613
	12.7	660

In this paper we do not consider the problem of the mode of PCs or metal-initiator ignition. This technical problem may be solved easily by an electric impulse addressed to the preset points in the preset time. If the ignition temperature of the concrete PC or metal-initiator is too high (higher than 1330–1500 K) one may apply an intermediate PC with a considerably lower ignition temperature even if its calorific value is rather lower (e.g. ferrocerium flames up very easy and it is applied as flint in lighters).

4. Conclusions

The main troubles at the launch vehicles exploitation responsible for the most significant negative impacts on the environment are described. Analysis of the known solutions to involve the unused earlier residues of liquid propellant into the combustion process has been carried out. Analysis of the ways to avoid re-entry of the man-made long-measuring separated parts of space launch vehicles was carried out. The proposals to use pyrotechnic compositions like thermites for fairing leaves burning at their re-entry in the atmospheric section of the descent trajectory have been analyzed. Some new pyrotechnic compositions for the assigned task solution have been proposed. The possibility to use highly inflammable metals and alloys as the heat source for warming-up the fairing leaves has been considered.

Acknowledgements

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