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ASSESSMENT OF THE POSSIBILITY OF USING POLYMERS IN THE BODIES OF PROMISING LAUNCH VEHICLES BASED ON THE HEAT RESISTANCE FACTOR

One of the possible ways to solve the problem of quick and low-cost payloads to low Earth orbits is the creation of ultralight rockets that use new construction materials, in particular, synthetic polymers. A promising approach to creating a launch vehicle of this type is the concept of a burnt rocket, the body of which is made of thermoplastic polymer materials. At the same time, the practical implementation of such a launch vehicle requires additional research, in particular, the possible process of premature destruction of the structure due to aerodynamic heating. In this work, the heat resistance of polymer bodies of a new type of ultralight launch vehicles during flight in the atmospheric part of the trajectory was evaluated. For mathematical modeling of heating processes, we used the results of experimental studies of the thermodynamics of polyethylene and polypropylene during heating. These results allowed us to propose a mathematical model for calculating the process of heating polymer shells. The dynamics of the temperature fields during movement along the given trajectory of the launch vehicle in the atmospheric stage have been determined. It was established that under the given trajectories, both considered materials satisfy the conditions of heat resistance. The influence of temperature on the reduction of the strength characteristics of polymer bodies is shown, and the necessary thicknesses of the walls of the body shells, which should prevent deformation of the structure during aerodynamic heating, are determined. So, for the first time, the possibility of making rocket bodies from thermoplastic polymer materials has been theoretically substantiated.

Keywords: *ultralight LV, polymer bodies, atmosphere part of flight, polyethylene, polypropylene, heat resistance.*

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INTRODUCTION

The demand for ultra-light launch vehicles is one of the trends of the modern space launch market, which is rapidly developing [8]. This is primarily due to the need to inject a large number of small satellite systems into orbit [3]. The use of heavy launch vehicles does not allow solving such tasks operationally. Therefore, engineers and manufacturers of space equipment are looking for new technical solutions to create cheap and reliable means of delivering nano-, pico-, and femto-satellites to low Earth orbits. One of the approaches to the creation of ultra-light launch vehicles is the use of lightweight structural materials, in particular polymers.

Polymer composites are widely used in the aerospace industry, but mainly as part of composite materials of individual structural elements or thermal protection [13, 22]. The idea of using thermoplastics to create the bodies of ultra-light launch vehicles was considered in [28, 29]. The polymer shell of the rocket body is, at the same time, fuel for the engine. In practical terms, the realization of a polymer launch vehicle became possible thanks to the creation of a special type of rocket engine on polymer fuel [31]. The proposed approach is promising because of the low cost, low mass, low thermophysical coefficients, etc., and creates a number of advantages compared to traditional structural materials. An important characteristic of polymers is their high energy characteristics, which are the basis for their use as rocket fuel [14, 15, 21, 30]. Therefore, solid hydrocarbon polymers are an acceptable substance for the manufacture of new ultralight rockets, which is the theoretical basis for the creation of combustible rockets from polymer bodies [32]. Such rockets acquire special value in terms of the space debris problem [7, 9], since burned tanks do not increase man-made pollution of Earth's orbits, unlike traditional launch vehicles. Such rockets can also be used as suborbital rockets and for launches into critically low Earth's orbits [26].

At the same time, it should be noted that in the atmospheric part of the trajectory, such LVs will be under the influence of heat loads due to aerodynamic heating. The choice of materials for the bodies of traditional LVs is usually based on the goal of reducing the weight of the structure, as well as technological requirements, physical and mechanical characteristics, cost, etc. But the main criterion, as a rule, is the minimum mass criterion [1]. Processes of thermal destruction of traditional structural materials used in aerospace engineering and their behavior under mechanical and thermal loads are well studied in the literature, for example [2, 4, 9, 17]. It should be noted that during the launch of launch vehicles, the bodies of which are made of traditional structural materials, the process of aerodynamic heating is not of critical importance for strength. However, the use of thermoplastic polymers requires additional research into possible thermal degradation of the material in the atmospheric part of the trajectory. The purpose of this work is to evaluate the thermal fields in the polymer shell of rockets during aerodynamic heating on the atmospheric part of the trajectory and to evaluate their influence of temperature on the strength characteristics of bodies made of various thermoplastic materials. So, the paper examines and compares the effect of aerodynamic heating on the heat resistance of fuel rocket bodies made of polyethylene and polypropylene.

PROBLEM STATEMENT

In work [5], theoretical calculations of the trajectories of a rocket with a polyethylene body and thermal loads during passage through the lower layers of the atmosphere were performed. Based on the data of this work, the methodology for calculating the aerodynamic heat load [6] and the parameters of the standard atmosphere [18], the initial data for calculating the heat loads on the body were selected. Figure 1 shows the change in flight parameters: altitude, Mach number, heat flow due to aerodynamic heating, as well as heat flow due to solar radiation [16] in the atmospheric part of the flight of a polymer rocket with a diameter of 0.3 m and an initial g-load of 1.2.

As can be seen from Fig. 1, the maximum heat loads correspond to the altitude range of 20...60 km. Under the influence of intense heat flows, thermoplastic materials, including polyethylene and polypropylene, can heat up, which leads to a decrease in mechanical characteristics and possible deformation of the body shell. When polymer shells are heated, a number of homogeneous and heterogeneous chemical reactions and phase transformations can begin,

which are accompanied by heat absorption and mass loss. Therefore, in mathematical modeling, additional terms in the energy equation describing processes of volumetric heat absorption should be taken into account. The processes of thermal depolymerization of thermoplastic polymers are well studied in a wide range of temperatures from room temperature [23, 25]. According to [25], the rate of polymer decomposition is determined by the kinetic equation

$$-\frac{d\rho}{d\tau} = B\exp\left(-\frac{E}{RT}\right)\rho, \qquad (1)$$

where ρ is the density, τ — time, B — pre-exponential multiplier, E — activation energy, R — gas constant, T — temperature.

The corresponding heat flows can be described by the formula

$$q_v(r) = \frac{B\Delta Q\rho}{\lambda}\exp\left(-\frac{E}{RT}\right), \qquad (2)$$

where ΔQ is the heat of phase transformation of the material (thermal destruction), λ is the coefficient of thermal conductivity.

Therefore, in order to assess the effect of temperature on the strength characteristics of polymer shells, it is necessary to study the thermodynamic processes that take place during the heating of polyethylene and polypropylene, determine the heat of phase transformations ΔQ, calculate the temperature fields, and determine the decrease in the mechanical characteristics of materials due to thermal effects.

EXPERIMENTAL DETERMINATION OF THE THERMODYNAMICS OF POLYMER SHELLS DURING HEATING

To determine ΔQ, experimental studies were carried out on the basis of the center for collective use of scientific equipment "Innovative technologies in the rocket and space industry" at Oles Honchar Dnipro National University (Dnipro, Ukraine). The heat value of the phase transformation was determined by the method of differential thermal analysis (DTA) [20], which is based on measuring the temperature difference between the substance under investigation and an inert standard using a differential thermocouple. This makes it possible to detect thermal effects in the substance under investigation. A high-precision analyzer STA 6000 was used to conduct the ex-

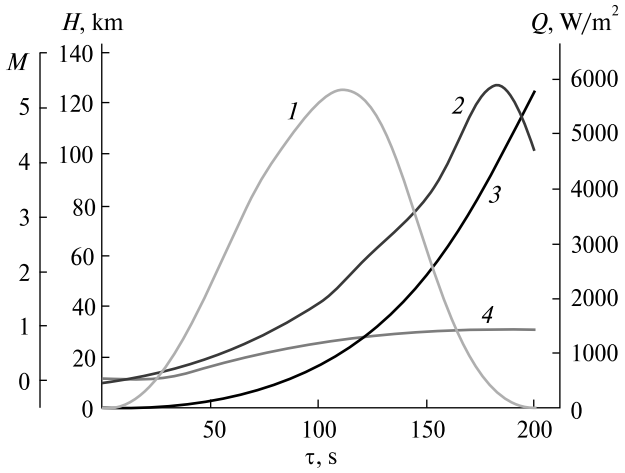

Figure 1. Flight parameters of a polymer rocket accepted for calculation

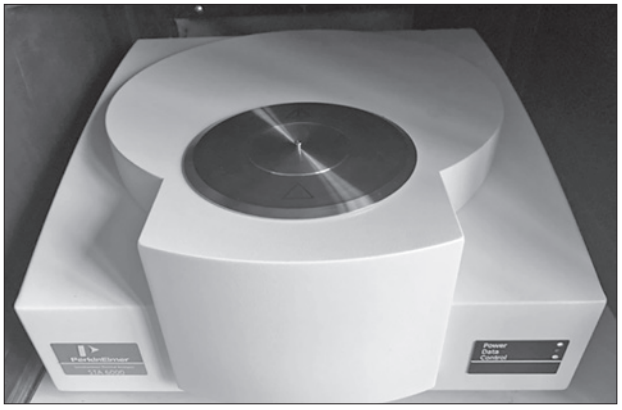

Figure 2. General view of STA-6000 analyzer

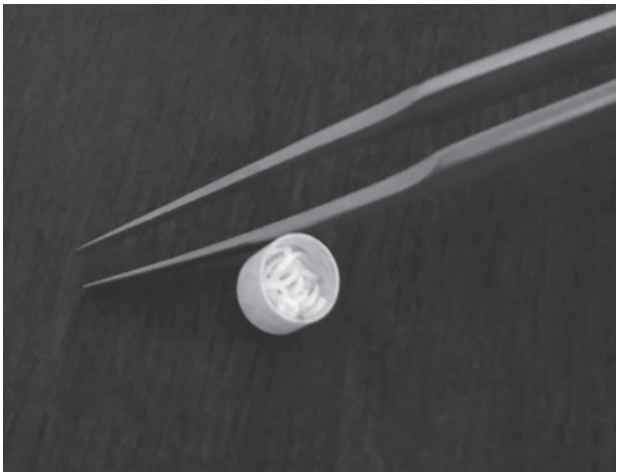

Figure 3. An experimental sample of polyethylene in a crucible

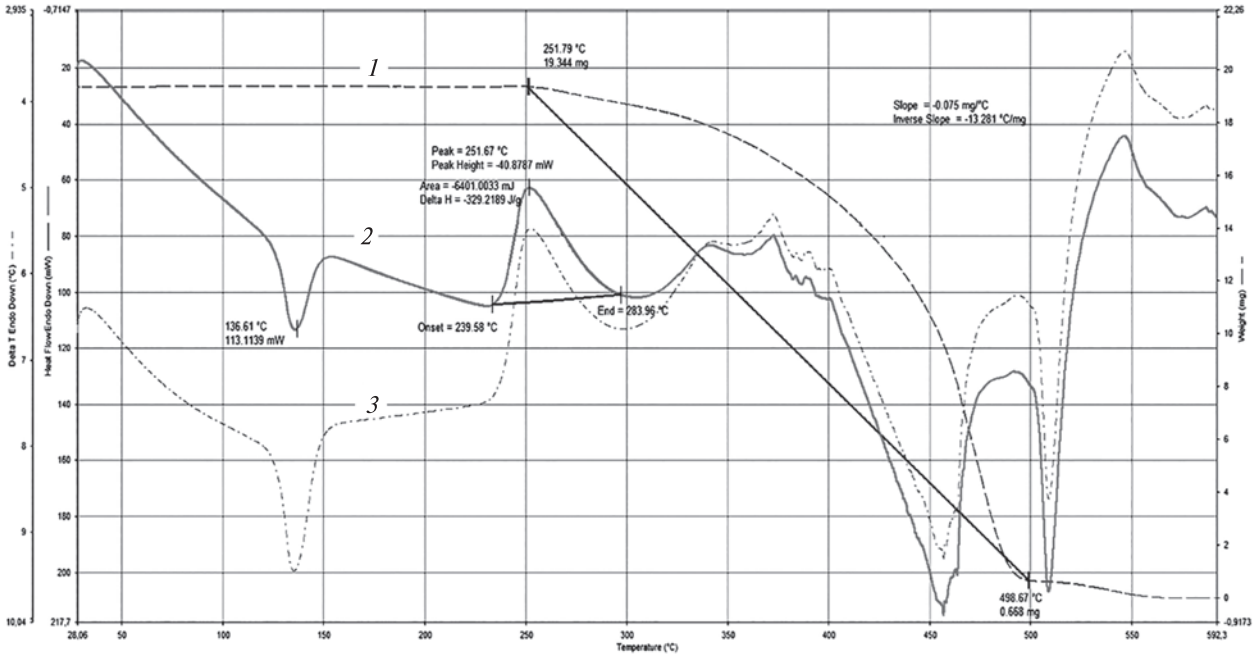

Figure 4. Example of a thermogram for heating a sample of high-density polyethylene: *1* — curve of thermogravimetric analysis, *2* — thermodifferential analysis, *3* — differential calorimetry

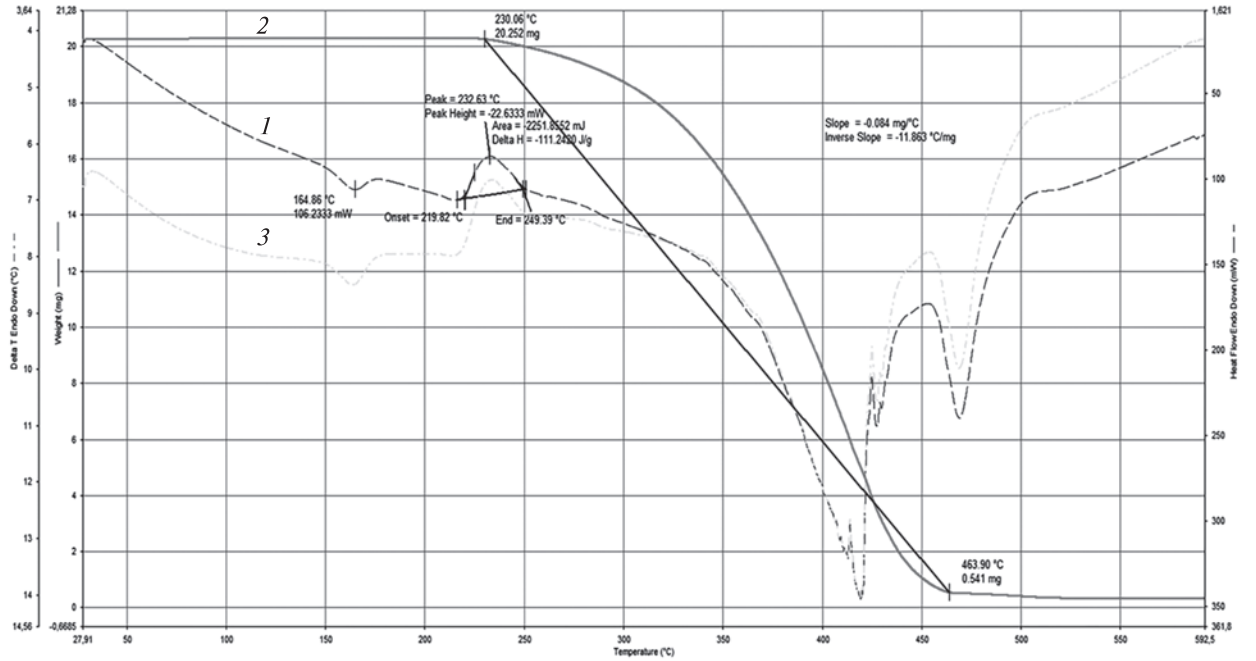

Figure 5. Example of a thermogram for heating a grey polypropylene sample: *1* — curve of thermogravimetric analysis, *2* — thermodifferential analysis, *3* — differential calorimetry

periments, which allows simultaneous thermogravimetric, differential thermal analysis, and differential scanning calorimetry. The general view of the analyzer is presented in Figure 2. The objects of the study were samples of high-density polyethylene and grey polypropylene, which were placed in the crucible of the analyzer shown in Figure 3.

The research was carried out under the following conditions: at the beginning of the experiment the temperature of the furnace was kept constant at 30 °C for 3...5 minutes, then the temperature changed in the range from 30 to 600 °C at a rate of 10 °C/min. The system was filled with argon, which excludes the possibility of accidental oxidation of the studied materials.

Figure 4 and Figure 5 show examples of thermograms obtained as a result of experiments. Figures 4, 5 present curves of thermogravimetric analysis (1), thermodifferential analysis (2), and the curve of differential calorimetry (3), which respectively show changes in the mass of the high-density polyethylene sample, the heat flow, and the temperature difference between the sample and the reference body during heating. The resulting curves were processed using specialized software. Unlike materials that sublimate, depolymerization of polymers occurs not only on the surface but in some layer of finite thickness near the surface.

From the analysis of the curves, it was established that the temperature at which structural changes begin (melting point) in materials is 136 °C (409 K) for polyethylene and 164 °C (437 K) for polypropylene. From the analysis of the thermogravimetric curve, it can be seen that active mass loss of polyethylene begins at a temperature of 251 °C (524 K), for polypropylene at 230 °C. With a temperature of 550 °C (823 K), complete gasification of polyethylene occurs. The corresponding value for polypropylene is 500 °C (773 K). Using DTA curves, the heat effect of thermal destruction was determined, as the area of the figures described by the peaks of the heat flow curves. So, on the basis of experimental results and literary data [24], the initial data for the calculation were determined (Table 1).

Table 1. **Parameters for calculation**

Material	Polyethylene	Polypropylen
Density r, kg/m^3	930	920
Thermal conductivly l, W/(m·K)	0.335	0.12
Thermal capacity *c*, J/(kg·K)	$1.94\cdot10^3$	$2.5\cdot10^3$
Ratio E/R, K	$24\cdot10^3$	$27.5\cdot10^3$
B, s^{-1}	$4\cdot10^{11}$	$7\cdot10^{14}$
Melting point, K	409	437
Full gasification point, K	823	773
Heat of thermal destruction, ΔQ, J/kg	$4200\cdot10^3$	$2400\cdot10^3$

MATHEMATICAL MODELING

The mathematical model of heat transfer in the cylindrical shells of the LV body during movement on the atmospheric part of the trajectory in a one-dimensional formulation has the form

$$c\rho\frac{\partial T}{\partial \tau}=\frac{1}{r}\frac{d}{dr}\left(\lambda r\frac{dT}{dr}\right)-q_v(r),$$

$$\tau>0,\quad R_1\le r\le R_2, \tag{3}$$

$$T\big|_{\tau=0}=T_o, \tag{4}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=R_1}=0,\ \lambda\left.\frac{\partial T}{\partial r}\right|_{r=R_2}=-q(\tau), \tag{5}$$

here T_0 is the initial temperature of the shell, R_1, R_2 are the inner and outer radii of the shell.

The source term in (3) is determined by expression (2), and the right-hand sides of the second equality (5) are determined according to the heat flow function presented in Figure 1. The necessary initial data for the calculation are given in Table 1.

Task (3)—(5) was solved numerically. Figure 6, *a* shows the results of calculating the temperature fields in the polyethylene cylindrical wall during the LV movement along the trajectory described by the data in Figure 1. A similar calculation for a polypropylene wall is shown in Figure 6, *b*.

As can be seen from Figure 6, the outer surface of polypropylene walls heats up during flight in the atmosphere a little more than polyethylene walls. This is due to the lower thermal conductivity of polypropylene than polyethylene. The temperature of the outer surface of the wall at the moment after 200 s (altitude of 125.3 km) is 375 K for polyethylene and 419 K for polypropylene. Therefore, for both materi-

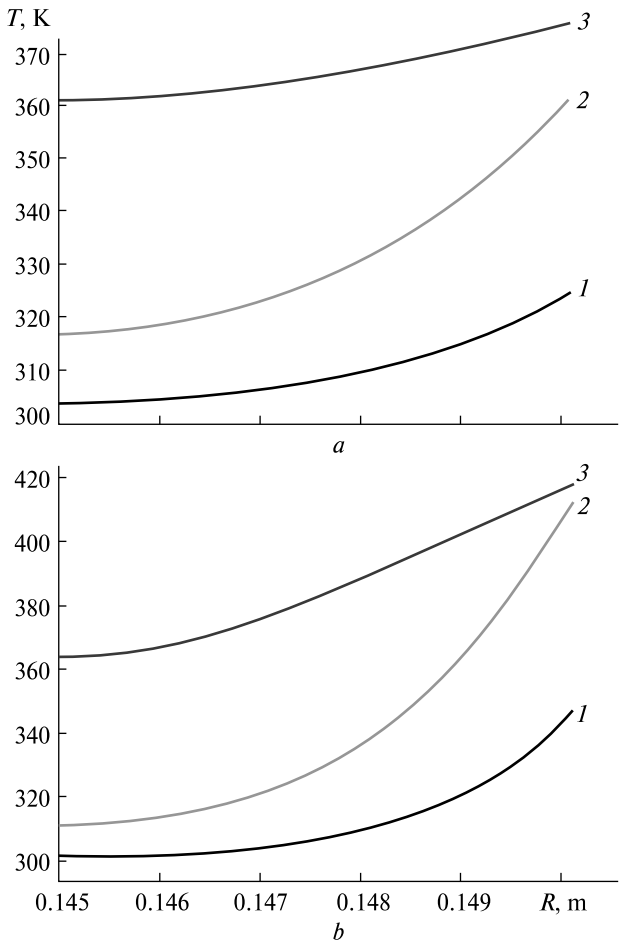

Figure 6. Temperature distribution in the polyethylene shell (*a*) and in the polypropylene shell (*b*) at different moments of time: *1* — 60 s, *2* —100 s, *3* — 200 s

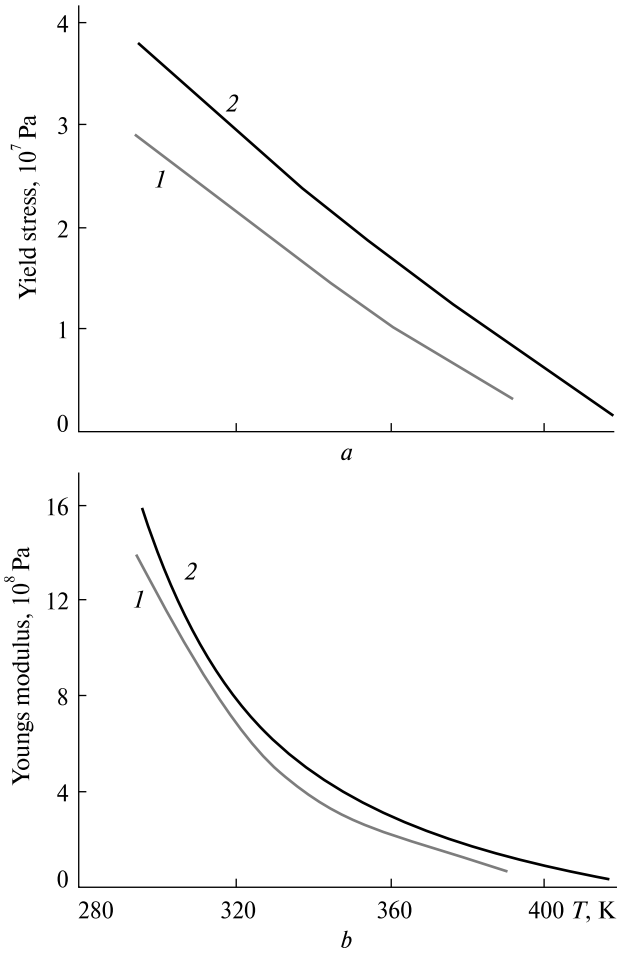

Figure 7. Dependence of yield strength (*a*) and of Young's modulus (*b*) on temperature for: *1* — polyethylene, *2* — polypropylene

als, the surface temperature remains lower than the temperature at the beginning of thermal destruction and mass loss.

It should be noted that the LV may be subjected to various loads during flight, leading to a loss of stability. The internal pressure was considered only herein. Torsion, bending, and other types of loads are not considered and should be the subject of further research.

The strength characteristics of solid hydrocarbon polymers are about an order of magnitude lower than the strength of structural aluminum alloys and depend on density, molecular weight, temperature, condition, etc. In particular, the yield strength of aluminum alloy AmG-6, which is used in aviation and rocket technology, reaches 130 MPa [19]. The problem arises of choosing the wall thickness of the polymer walls of the LV bodies, which ensure the proper strength of the structure during movement in the atmospheric stage.

From the point of view of the strength of thermoplastic materials, an important role is played by the yield strength, which is defined as the conditional stress σ at which the material begins to deform without a noticeable increase in load. Below, the dependencies are presented of yield strength (Figure 7, *a*) and Young's modulus (elasticity) (Figure 7, *b*) on temperature for high-density polyethylene and polypropylene according to the data in works [11, 12].

As can be seen from the data in Figure 7, the strength characteristics (yield strength, Young's modulus) of polypropylene are higher than those of polyethylene. Based on the data presented, it can be stated that the yield strength of polyethylene decreases by 4.7 times when the temperature rises to 375 K. For polypropylene, this decrease is more than 8.5 times when the temperature rises to 410 K. This creates conditions for deformation of the structure and premature destruction. The thickness of cylindrical shells required for strength requirements, assuming that the main force factor is internal pressure, can be determined by the following formula [27]

$$\delta = \frac{PR_2}{\sigma} f , \qquad (6)$$

here δ is the shell thickness, P — internal pressure, $f = 1.5$ — safety factor.

Table 2 shows the results of calculating the required wall thicknesses of the shells under the condition of heating at an internal pressure of 1 MPa an external radius of 0.3 m and a temperature of 405 K. For elements that work for strength with mainly tensile forces, the specific strength index (the ratio of the yield strength to its density) is used. For plastic materials, instead of the specific strength index, the specific fluidity index (the ratio of the yield strength to its density) is used. In the case when the bearing capacity of the structure is determined by stability, an additional indicator is introduced — specific stiffness. For comparison, the data for aluminum alloy AmG-6, which is used as a structural material for rocket fuel tanks [19]. Taking into account the relatively significant thickness of the walls of LV body and the work, mainly on strength, we will limit ourselves to the indicator of maximum strength in the form of specific fluidity for polymers. As a specific strength, we mean the ratio of the corresponding strength to the density of the material. To compare the strength of different materials, the following strength parameters are used: yield strength for polymers and tensile strength for AmG-6

$$\bar{\sigma} = \sigma / \rho .$$

Table 2. **The wall thickness of cylindrical shells**

Material	Specific strength $\bar{\sigma}$, kN·m/kg	Required wall thickness δ, m
High-density polyethylene	2.72	$7.2 \cdot 10^{-3}$
Polypropylene gray	6.67	$1.8 \cdot 10^{-2}$
Aluminum alloy AmG6	85.7	$1.9 \cdot 10^{-3}$

As can be seen from the data in Table 2, polypropylene shells require a greater thickness, although the strength characteristics of polypropylene are higher than those of polyethylene. This is due to higher surface heating temperatures, which leads to a greater drop in strength characteristics. The use of polymer materials requires an increase in the thickness of the body shells compared to AmG-6 alloy in terms of strength. At the same time, the specific strength of polymer shells decreases by an order of magnitude, which should lead to an increase in body weight. Given that in burnt rockets, the rocket body is a fuel charge, increasing the thickness of the shells will ensure the necessary fuel supply. For burnt rockets, the mass of the structure is not passive, as it is also the mass of fuel consumed during engine operation. Therefore, the mass of the structure at the end of the active flight part is not included in Tsiolkovsky's formula for ideal speed. Thus, the presented results allow us to state that the temperature and strength characteristics of thermoplastic polymers ensure the heat resistance of the bodies of new ultra-light launch vehicles during aerodynamic heating.

CONCLUSIONS

The work investigates the processes of aerodynamic heating of the surface of launch vehicle bodies made of thermoplastic materials: polyethylene and polypropylene. As a result of the performed experimental and theoretical studies, it was established that thermoplastic materials meet the conditions of heat resistance during movement in the atmospheric part of the flight path. Temperatures arising as a result of aerodynamic heating in the atmospheric part of the trajectory do not exceed the critically permissible ones. The decrease in the strength characteristics of such materials, when heated, requires an increase in the thickness of the body walls of the launch vehicle in comparison with traditional aluminum alloys. It was determined that thicknesses of $7.2 \cdot 10^{-3}$ — $1.8 \cdot 10^{-2}$ m allow us to ensure adequate strength while reducing the specific strength of materials. Among the considered materi-

als, attention should be paid to polyethylene, which heats up less due to aerodynamic heating.

Thus, from the point of view of heat resistance, the possibility of using thermoplastic polymer materials (polyethylene, polypropylene) as structural materials for the manufacture of rocket bodies is shown.

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REFERENCES

1. Alekseev Ju. S., Dzhur O. E., Kulik O. V., Kuchma L. D. (2007). *Rocket and space aircraft production technology.* Dnepropetrovsk: Art-Press, 477 p. [in Russian]
2. Balakrishnan Deependran, Kurian Job. (2014). Material Thermal Degradation Under Reentry Aerodynamic Heating. *J. Spacecraft and Rockets*, **51**, 1319—1328. https://doi.org/10.2514/1.A32712
3. Curzi G., Modenini D, Tortora P. (2020). Large Constellations of Small Satellites: A Survey of Near Future Challenges and Missions. *Aerospace*, **7**(9), 133. https://doi.org/10.3390/aerospace7090133
4. Dreus A., Dron M., Gubin O., Dubovik L. (2022). Modeling of processes of aerodinamichesky heating and fusion of space objects in atmosphere of the earth. *System Design and Analysis of Aerospace Technique Characteristics,* **30**(1), 20—34. https://doi.org/10.15421/472203
5. Dreus A., Yemets V., Dron M., Yemets M., Golubek A. (2022). A simulation of the thermal environment of a plastic body of a new type of launch vehicle at the atmospheric phase of the trajectory. *Aircraft Engineering and Aerospace Technology*, **94**(4), 505—514. https://doi.org/10.1108/AEAT-04-2021-0100
6. Dron M., Dreus A., Golubek A., Abramovsky Y. (2018) Investigation of aerodynamic heating of space debris object at reentry to earth atmosphere. *Proc. 69th Int. Conf. IAC-18, A6.2,* Bremen, Germany.
7. Dron M., Golubek A., Dreus A., Dubovik L. (2019). Prospects for the use of the combined method for deorbiting of large-scale space debris from near-earth space. *Space Science and Technology,* **25**(6), 61—69. https://doi.org/10.15407/knit2019.06.061
8. Dron M., Hilorme T., Golubek A., Dreus A., Dubovik L. (2022). Determining the performance indicators of employing combined methods for removing space objects from near-earth orbits. *Eastern-European J. Enterprise Technologies,* **1**(3-115), 6—12. https://doi.org/10.15587/1729-4061.2022.253096
9. Dzhur Y. O., Kalinina N. E., Dzhur O. Y., Kalinin O. V., Nosova T. V., Mamchur S. I. (2021). Improvement of properties of deformed aluminum alloys modified by nanocompositions. *Space Science and Technology*, **7**(6), 98—104. https://doi.org/10.15407/knit2021.06.098 10
10. Golubek A., Dron M., Dubovik L., Dreus A., Kulyk O., & Khorolskiy P. (2020). Development of the combined method to de-orbit space objects using an electric rocket propulsion system. *Eastern-European J. Enterprise Technologies,* **4**(5—106), 78—87. https://doi.org/10.15587/1729-4061.2020.210378
11. Hartmann B., Lee G. F., Cole R. F. (1986). Tensile yield in polyethylene. *Polymer Engineering and Sci.*, **26**(8), 554—559. doi:10.1002/pen.760260806
12. Hartmann B., Lee G. F., Wong W. (1987). Tensile yield in polypropylene. *Polymer Engineering and Sci.*, **27**(11), 823—828. doi:10.1002/pen.760271109
13. Irving P. E., Soutis C. (2019). *Polymer composites in the aerospace industry.* Woodhead Publishing.
14. Kositsyna O. C., Dron' M. M., Yemets V. V. (2020). The environmental impact assessment of emission from space launches: the promising propellants components selection. *J. Chemistry and Technologies,* **28**(2), 186—193. https://doi.org/10.15421/082020
15. Kositsyna O., Dron M., Kulyk O. (2021) Determining energetic characteristics and selecting environmentally friendly components for solid rocket propellants at the early stages of design. *Eastern-European J. Enterprise Technologies,* **6**(6-114), 6—14. https://doi.org/10.15587/1729-4061.2021.247233
16. Krasnov N. F. (1976). *Aerodynamics. Part 2. Methods of aerodynamic calculation*. Moscow: Graduate School, 368 p. [in Russian].
17. Lapkhanov E., Palii O., Golubek A. (2022). Determining the degree of effect of heat flows on the deformation of the shell of a space inflatable platform with a payload. *Eastern-European J. Enterprise Technologies*, **5**(1-119), 6—16. https://doi.org/10.15587/1729-4061.2022.266161

18. Leslie F. W., Justus C. G. (2008). The NASA MSFC Earth global reference atmospheric model-2007 Version (No. NASA/TM-2008-215581).
19. Linnik A. K. (1994). *Design of liquid-propellant ballistic missile bodies*. Dnipro: Dnipropetrovsk Univ. publ. [in Russian]
20. Menczel J. D., Prime R. B. (2009). *Thermal analysis of polymers: fundamentals and applications.* John Wiley & Sons.
21. Okninski A., Kopacz W., Kaniewski D., Sobczak K. (2021). Hybrid rocket propulsion technology for space transportation revisited — propellant solutions and challenges. *FirePhysChem*, **1**(4), 260—271. https://doi.org/10.1016/j.fpc.2021.11.015 18
22. Pastore R., M. Albano, A. Delfini, F. Santoni, M. Marchetti. (2021). Thermoplastic Polymeric Materials for Spacecraft Applications: Flame Retardant Properties and UV/AtOx Aging Analysis. *Appl. Sci.,* **11**(3), 949. https://doi.org/10.3390/app11030949
23. Pielichowski K., Njuguna J., Majka T. M. (2022). *Thermal degradation of polymeric materials*. Elsevier, 378 p.
24. Polezhaev Yu. V., Yurevich F. B. (1976). *Thermal protection. Under the editorship of A. V. Lykov*. Moscow: Energy, 392 p. [in Russian].
25. Ranzi E., Dente M., Faravelli T., Bozzano G., Fabini S., Nava R., et al. (1997). Kinetic modeling of polyethylene and polypropylene thermal degradation. *J. Analytical and Applied Pyrolysis*, **40–41**, 305—319. https://doi.org/10.1016/s0165-2370(97) 00032-6
26. Shoyama T., Wada Y., Matsui T. (2022). Conceptual study on low-melting-point thermoplastic Fuel/Nitrous oxide hybrid rockoon. *J. Spacecraft and Rockets,* **59**(1), 286—294. https://doi.org/10.2514/1.A35040
27. Vullo V. (2014). *Circular Cylinders and Pressure Vessels*. Springer Cham. https://doi.org/10.1007/978-3-319-00690-1
28. Yemets M., Yemets V., Harkness P., Dron' M., et al. (2018). Caseless throttleable solid motor for small spacecraft. *Proc. 69th Int. Astronautical Congress.* Bremen, Germany, 10924—10933.
29. Yemets V. V. (2008). Areas of expedient use of launch vehicles with polietilen tanks that burn out. *Space Science and Technology*, **14**(1), 17—24.
30. Yemets V. V., Dron M., Kositsyna O. C. (2019). Estimation of the Possibilities for Using the Solid Hydrocarbon Fuels in Autophage Launch. *J. Chemistry and Technologies*, **27**(1), 58—64. https://doi.org/10.15421/081906
31. Yemets V., Dron M., Pashkov A. (2020). Autophage engines: Method to preset gravity load of solid rockets. *J. Spacecraft and Rockets*, **57**(2), 309—318. https://doi.org/10.2514/1.A34597
32. Yemets V., Dron M., Pashkov A., Dreus A., Kositsyna Y., Yemets M., Dubovyk L., Kostritsyn O., Zhuravel P. (2020). Method to preset G-load profile of launch vehicles. *Proc. Int. Astronautical Congress, IAC*.

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ОЦІНКА МОЖЛИВОСТІ ЗАСТОСУВАННЯ ПОЛІМЕРІВ В КОРПУСАХ ПЕРСПЕКТИВНИХ РАКЕТ-НОСІЇВ ЗА ФАКТОРОМ ТЕПЛОСТІЙКОСТІ

Одним із можливих шляхів вирішення проблеми оперативного і дешевого виведення корисних вантажів на низькі навколоземні орбіти є створення надлегких ракет-носіїв, що використовують нові конструкційні матеріали, зокрема синтетичні полімери. Перспективним підходом до створення такої ракети-носія є концепція спалимої ракети, корпус якої зроблено з термопластичних полімерних матеріалів. Водночас її практична реалізація потребує проведення додаткових досліджень, пов'язаних з можливим процесом передчасного руйнування конструкції внаслідок аеродинамічного нагрівання. У роботі оцінено теплостійкість нового типу полімерних корпусів надлегких ракет-носіїв під час польоту на атмосферній ділянці траєкторії. Представлено результати експериментальних досліджень термодинаміки при нагріванні поліетилену і поліпропілену, які було розглянуто для математичного моделювання процесів нагріву. Запропоновано математичну модель для розрахунку процесу нагрівання полімерних оболонок. Визначено динаміку температурних полів під час руху ракети-носія по заданій траєкторії на атмосферній ділянці. Встановлено, що на заданих траєкторіях обидва розглянутих матеріалів задовольняють умову теплостійкості. Показано вплив температури на зменшення міцнісних характеристик полімерних корпусів. Як показник міцності для термопластичних полімерних матеріалів розглядається питома міцність у вигляді відношення межі плинності до щільності матеріалу. Визначено необхідні товщини стінок оболонок корпусів, що мають запобігти деформації конструкції при аеродинамічному нагріванні. Полімерний корпус спалимої ракети не є тонкостінною оболонкою. Проте маса конструкції не є пасивною, оскільки це також маса палива, що споживається двигуном. Отже, вперше теоретично обґрунтовано можливість виконання корпусів спалимих ракет з термопластичних полімерних матеріалів.

***Ключові слова*:** надлегкі РН, полімерні корпуси, атмосферна ділянка польоту, поліетилен, пропілен, теплостійкість.