https://doi.org/10.33271/nvngu/2023-5/072

S. S. Vasyliv[1],
orcid.org/0009-0000-0815-6323,
N. S. Pryadko[*1],
orcid.org/0000-0003-1656-1681,
S. G. Bondarenko[2],
orcid.org/0000-0001-9590-4747

1 – Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and State Space Agency of Ukraine, Dnipro, Ukraine
2 – Oles Honchar Dnipro National University, Dnipro, Ukraine
[*] Corresponding author e-mail: np-2006@ukr.net

COMBUSTION AND DETONATION OF PASTE FUEL OF ROCKET ENGINE

Purpose. Confirmation of the possibility of using a paste fuel based on ammonium perchlorate in a rocket engine and identifying the characteristics of its combustion.

Methodology. Previous experimental studies on the burning of paste fuel in a constant pressure bomb determined the burning rate at different pressures. The stability of deflagration combustion without transition to the detonation mode was confirmed. An explosion occurred during the fire test of the engine model on paste-like fuel. The analysis of the causes of the explosion made it possible to put forward a hypothesis about the enrichment of the paste fuel with ammonium perchlorate, which created the prerequisites for its detonation. The conducted additional experiments showed a change in the combustion mode when enriching paste fuel with ammonium perchlorate.

Findings. Theoretical and experimental studies have shown the possibility of obtaining detonation fuel based on the enrichment of paste fuel with ammonium perchlorate. It has been proven that, under certain production conditions, paste fuels can detonate, which opens up a new way of using such fuels for rocket engines. The conditions for the transition of the burning mode of pasty fuel from deflagration to detonation combustion are determined. The speed of the engine element during the explosion was evaluated and it was shown that during explosive combustion due to the large area and, accordingly, the mass flow, it is not possible to obtain a pressure value that could ensure the movement parameters registered in this engine design.

Originality. Another criterion is established of engine operability when designing an engine on paste fuel. The effect of enrichment of pasty fuel with ammonium perchlorate during its flow through the supply system at the time of start-up was revealed.

Practical value. The given information makes it possible to improve the design of the engine on paste fuel and to modernize the stand for its tests.

Keywords: *critical detonation diameter, binder concentration, filler, paste rocket fuel, ammonium perchlorate*

Introduction. Explosives have been used in industry for a long time. Their application has found not only in the mining industry, but also in rocket and space technology. For example, ammonium perchlorate is used as an oxidizer for solid rocket fuels. As a component of explosives for technologies where blast energy is used, ammonium perchlorate provides better energy characteristics than mixtures based on ammonium nitrate. But its mixtures are highly sensitive to impact and friction. As fuel, organic compounds are used – TNT, dinitronaphthalene, liquid nitro compounds, and inorganic substances such as carbon black, aluminum, or ferrosilicon, which are similar in composition and properties to ammonia-nitrite and were used for the same purposes. Also, perchlorate explosives that do not contain nitro derivatives at a density higher than 1–1.1 g/cm^3 have a decrease in detonation speed and susceptibility to a detonation pulse. Their disadvantage is that many organic substances (paraffin, ceresin) phlegmatize perchlorate mixtures and also, on the contrary, significantly increase sensitivity to impact and friction. Perchlorate explosives, also called shedites, were invented in England in 1897. They were used to equip some ammunition and explosive works until the middle of the *20th* century. In Japan, they were used under the name "Carlites" even longer. Currently, perchlorate explosive mixtures are used for highly specialized technological processes.

The problem and its connection with scientific and practical tasks. The trend of finding ways to reduce the cost of putting spacecraft into orbit has been observed for a long time. The directions that make it possible to do this relate to the simplification of production technology, the search for new materials, and the improvement of the engine energy characteristics. In addition, there are new technical solutions that make it possible to reduce the cost of space technology by combining the properties of various elements. Rocket engines on pasty fuel can be attributed to this category. The pasty fuel is in a separate tank and is fed into the combustion chamber due to fluidity, but its density is higher than that of liquid fuels [1]. Paste fuel is an unhardened mixed fuel with a similar chemical composition to solid fuel. When comparing engines with solid and pasty fuel, it is necessary to note their difference. The solid fuel has a simpledesign, is easy to start, and is easy to operate. The engine on pasty fuel has a higher coefficient of volume filling, it is possible to adjust the traction in a wide range and, the most importantly, with the possibility of multiple starts. With slightly lower energy characteristics, it has almost 1.5 times greater fuel density than liquid rockets. That is why it takes up less space.

Fuel based on ammonium perchlorate is prone to detonation. If it is hardened and the porosity is insignificant, then the critical size of detonation is of the order of more than 10 m. That is, for detonation to occur in the charge, the smallest size of the charge must be greater than 10 m. This size is larger than any engines in operation. Therefore, detonation does not occur in them. But when the fuel is not hardened, it can contain air bubbles, which significantly reduce the critical size of detonation. This allows the detonation to pass through the charge. Engines on paste-like fuel are promising power plants for the upper stages of rockets, booster units, and space vehicles. They are not mass-produced yet; the article is about experimental samples.

There are many difficulties on the way to creating such installations. The main problem is the design complexity of the supply valve, as well as the problem of extinguishing the combustion in the chamber and not spreading the flame front into the tank. In addition, there are problems with the properties of pasty fuel. One of the problems discovered experimentally is discussed in this paper.

Literature review. Ammonium perchlorate was used as an oxidizer in experimental studies. It belongs to the *2nd* class of explosive substances and is also used in the mining industry. Many publications have been written about the detonation of its mixtures with aluminum. In solid rocket fuel, in addition to ammonium and aluminum perchlorate, a binding component is used as an energy addition. Due to its properties, it acts also as a phlegmatizer, which by increasing the critical detonation size of mixtures based on ammonium perchlorate ensures convective combustion in solid-fuel rocket engines and, accordingly, their safe operation [2].

Formulation of the problem. The key element of a rocket engine on paste-like fuel is the filament block or the main supply valve, since it is responsible for extinguishing the combustion reaction and preventing its continuation in the pipeline. If this condition is not met, the engine loses the possibility of multiple starts and, accordingly, the advantage over a solid fuel engine. The conducted fire experiment, which ended in an explosion, showed the possibility of detonation in the paste that passed through the supply system. This is another problem on the way to creating an engine on pasty fuel that had to be solved. The article provides an analysis of possible causes of paste detonation during a fire test.

The purpose of the work is to confirm the possibility of using a pasty fuel based on ammonium perchlorate in a rocket engine and to identify the characteristics of its combustion.

Methods. The article provides an analysis of possible causes of paste detonation during a fire test. The tests were carried out in industrial conditions in the winter period. To increase fluidity, the stand was equipped with a thermostatic cabinet. The temperature of the paste before the tests was +25 °C. The stand is placed in a semi-closed box with a leaky ceiling.

During the experimental tests, several problems regarding the design of the engine installation and the methodology of the experiments were solved.

Results and discussion. Due to its properties, ammonium perchlorate is widely used in the mining industry, pyrotechnics, military, and space rocket technology. Mass industrial production was launched thanks to the First World War, which stimulated the chemical industry to find alternatives to pyroxylin gunpowder and explosives, for the production of which nitric acid is used. It is known about the possibility of combustion and detonation of mixtures based on ammonium perchlorate [3]. With the beginning of the Cold War between the USA and the USSR, an intensive search for solid fuel formulations that would allow the creation of missiles for submarines began. Many requirements were put forward for such installations, the main of which are high specific impulse and high fuel density to minimize the size of the rocket. Therefore, ammonium perchlorate has taken its place in a number of indispensable materials for rocket technology.

It is known that combustion, as well as detonation, occurs in charges with dimensions larger than critical ones. For deflagration combustion, these dimensions are much smaller than for detonation [4]. To ensure the efficiency of the engine installation, it is necessary that at the moment of stopping the supply of paste to the combustion chamber, the reaction stops and does not spread in the pipeline. This can be implemented with a valve or filament. In the design of the engine model, a filament was installed, which evenly distributed fuel, as well as a valve. The viscosity of the fuel was quite high and made it difficult to ensure the uniformity of the distribution of the fuel mass flow over the entire area of the filament et. Therefore, its design was made in the form of a set of washers with specially selected holes in the middle and different distances between the washers. The operation of the filament was tested experimentally on model paste and on fuel (Fig. 1).

The problem with the main valve is that particles of ammonium perchlorate get into the gap between the valve and the seat when it is closed [5, 6]. The impact pressing the valve against the seat can lead to their ignition and explosion. Therefore, a valve scheme with rotation of the flow part was used. It does not exclude similar phenomena either, but the contact area is much smaller and, accordingly, the probability of ignition and accident is also lower.

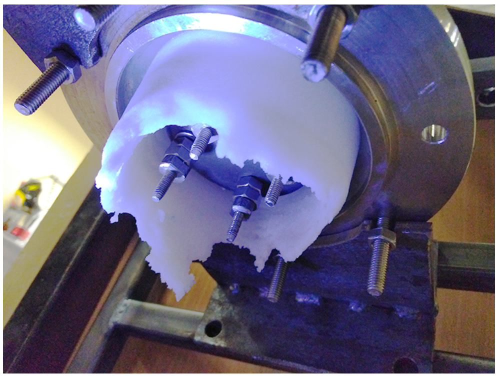
A spherical tank with a flexible split bottom was installed on the model engine installation, which contained 5 kg of pasty fuel (Fig. 2).

Refueling took place through a special refueling cylinder, inside which there was a piston. Due to the pressure of nitrogen, the paste from the cylinder entered the spherical tank. Nitrogen also supplied fuel from the tank to the model engine.

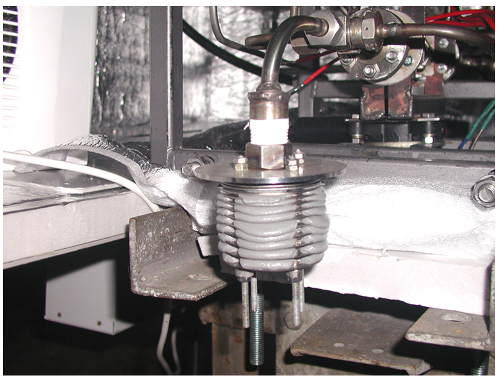
To ensure the specified temperature range, the bench-top installation was equipped with a thermostatic system.

The ignition test of the paste was carried out in the open air when it was in contact with an electric glow plug. At the same time, the candle was heated together with the paste applied to it. Ignition occurred a few seconds after the heating was turned on as the temperature rose.

During cold testing of the paste, the mass flow rate through the filament was determined at a pressure in the tank of 20 bar. At the same time, the mass consumption was 0.05 kg/s. Test-



a



b

Fig. 1. Casting of the filament with model (a) and working (b) paste

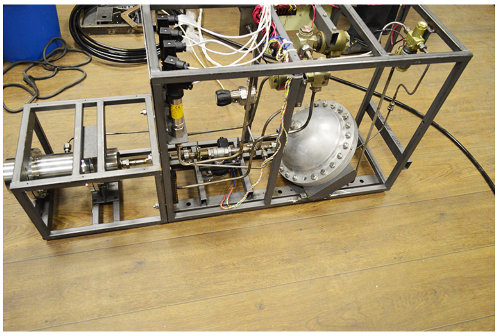


Fig. 2. Model engine installation

ing was carried out immediately before the fire test to ensure the same conditions of the experiment. The fire test ended with an accident and complete destruction of the bench installation (Fig. 3). Only the engine model, which was quite massive, remained without significant damage. The cyclogram of the tests provided for the heating of the candles 20 seconds before the start, filling the tank with nitrogen 10 seconds before the start, and at the time of the start, the main valve was opened.

The paste filled the filler in a few seconds when the pipeline was empty. After filling the tank with nitrogen, the main valve was turned on. The glow plugs were already heated. 3 seconds later, there was an explosion. The footage of the video registration showed that the camera with the nozzle unit was missing, and the front bottom with the filament was located on the damaged frame of the stand. At the same time, a fire was observed in the supply pipeline. Seconds later there was another explosion as the flame front traveled down the pipeline to the 5 kg fuel tank. In the nearby box, where the control panel and the data collection system were located, both explosions were felt at the same intensity, but at a greater distance the first explosion was felt stronger. The pressure sensor, whose measurement limit is 16 MPa, recorded a pressure jump of 16 MPa. The peculiarity of its operation is that it cannot digitize higher pressure values, and therefore shows only the limit value. The permissible overload is about 32 MPa. Inspection of the sensor after the tests showed that it had failed. Before contact with the heated surface in the chamber, there could be no more than 0.193 kg of fuel, of which 0.04 kg was in the chamber itself, and the rest (0.153 kg) was in the voids of the filament.

With normal combustion on the free surface of the paste coming out of the filament, the calculated pressure in the chamber is 1 MPa. The flange connection of the combustion chamber and the front bottom was calculated in such a way that the yield point of the gasket material was reached and an overpressure of 3 MPa was withstood while the bolts worked within the range of material proportionality. When the pressure was exceeded, the yield point σ of the bolt material was reached and, accordingly, the tightness of the joint was lost due to the appearance of a gap between its parts (Fig. 4).

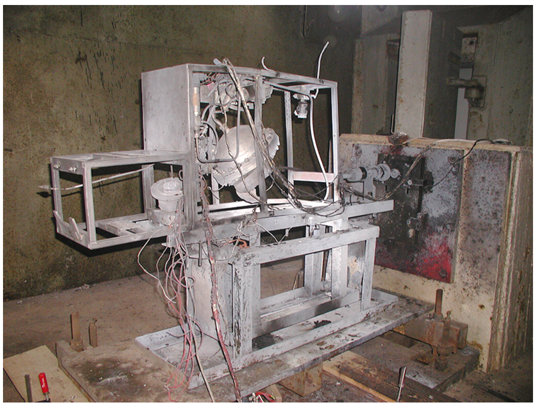


Fig. 3. Stand with a model engine installation after the accident

In the ideal case, when the paste flows out in the form of flat washers, the initial combustion area is 0.06989 m^2. At the same time, the mass of fuel that leaked from the filament is 0.04 kg, and its consumption is 0.654 kg/s. The pressure in the combustion chamber is determined by the formula [7]

$$p = \frac{\dot{m} \cdot \sqrt{R \cdot T}}{\frac{\pi \cdot d_{cr}^2}{4} \cdot A_k},$$

where $\dot{m}$ is the mass flow rate of the paste; $T = 2941$ K – the temperature; $R = 237.72$ J/kg · K – the gas constant of combustion products; d_{cr}^2 is the diameter of the critical section of the nozzle. It should be noted that there was no supersonic part of the nozzle, since in the first fire experiment it was necessary to determine only the consumption complex, which made it possible to determine the energy characteristics with any nozzle. The coefficient A_k, in turn, is determined by the formula [8]

$$A_k = \left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}}.$$

The pressure that can be reached under the specified initial conditions is $3.01 \cdot 10^7$ Pa, i. e. 10 times higher than that which the flange connection can withstand. When the initial mass of the paste that has flowed out of the filament is burned, the burning area decreases, accordingly, and the mass flow also decreases. Let us consider the case of instantaneous gas release at the initial moment of the experiment and analyze what speed

and the amount of fuel that was in the combustion chamber under these conditions could give the part of the engine that separated during the explosion. To do this, let us write down a simple model of movement dynamics according to the scheme illustrated in Fig. 5.

$$\frac{d^2x}{dt^2} = \frac{F}{m}.$$

The body is affected by the force of traction, which is caused by the outflow of gas from the engine through the nozzle only due to the mass, as well as the force caused by the pressure inside

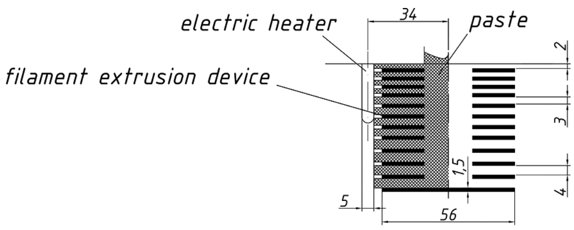


Fig. 4. Scheme of the filament extrusion device

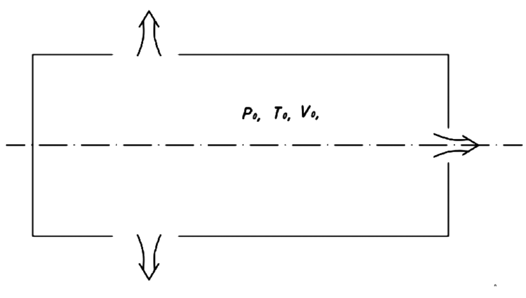


Fig. 5. Scheme of gas leakage from the engine

$$F = p \cdot \frac{\pi \cdot d_{ch}^2}{4} - \dot{m}_c \cdot U_{cr},$$

where d_{ch}^2 is the internal diameter of the combustion chamber; $\dot{m}_c$ – the mass flow of gas through the nozzle.

The critical speed is determined by the formula

$$U_{cr} = \sqrt{\frac{2k}{k+1} \cdot R \cdot T},$$

where k is the adiabatic coefficient; T – the gas temperature, which decreases as a result of adiabatic expansion. The pressure drop is determined from the Clapeyron-Mendeleev equation.

The time step was 0.0001 s. The results of the calculations are illustrated in Figs. 6, 7.

The maximum speed that can be obtained in the idealized case, when bolt breakage occurs at a pressure (Fig. 8) of 30.1 MPa, is 8.1 m/s (Fig. 7).

The mass of the nozzle block with part of the combustion chamber was 10.5 kg. The engine was installed strictly horizontally on the stand. During the explosion, part of the combustion chamber flew 11.5 m and fell by 0.5 m, leaving a mark on the wall of the box. The speed that was given to the body under these conditions is 36 m/s, and the flight time is 0.319 s, that is, the speed in the experiment was 4.4 times higher than the calculated one. If the explosion occurred according to the described scenario, the pressure in the chamber was correspondingly higher by the same number of times.

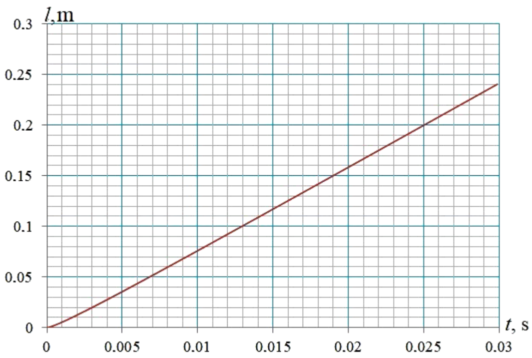


Fig. 6. Dependence of movement on time

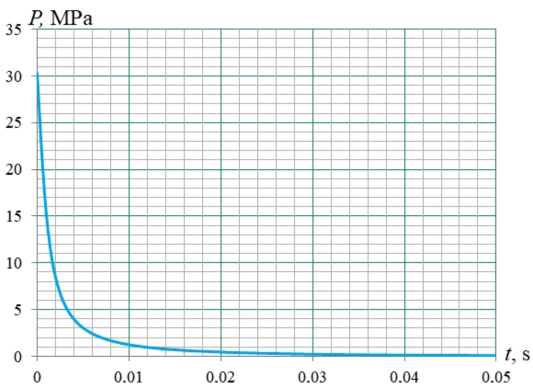


Fig. 7. Dependence of pressure on displacement

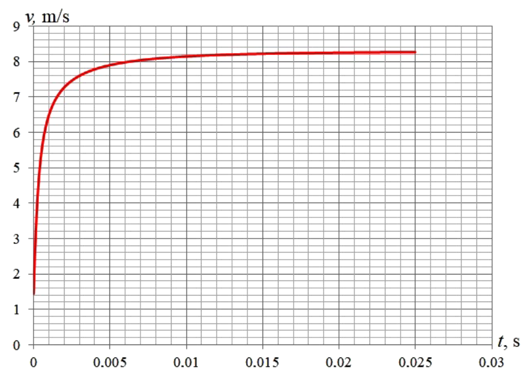


Fig. 8. Dependence of speed on time

It is obvious that such an order of values could be achieved only with the detonation of the paste [2]. The reasons for its occurrence cannot be the initial composition of the fuel since separate fire tests of the paste were conducted to determine the burning rate. In addition, the ignition of the paste was also checked immediately before the test and no deviations were found.

The composition of the fuel given in the table was typical, but in order to improve the rheological characteristics, technological additives were applied to it [9].

The likely cause of the explosion may be a decrease in the concentration of rubber, which also acts as a phlegmatizing addition. It is known that ammonium perchlorate mixed with aluminum can detonate within a fairly wide range of concentrations [7].

These scopes are even wider for porous bulk media [8]. This is manifested in the reduction of the critical diameter and the transition of combustion to detonation. For solid rocket fuel, the oxidizer of which is ammonium perchlorate, this parameter ranges from a few meters to tens of meters, because the binding component is polymerized, and the charges are usually pressed to avoid the appearance of voids.

But in our case, the paste was not hardened, and the possibility of the micro pore presence in the volume was not excluded. In addition, the area of the filament is quite large; therefore, passing through it, part of the rubber moistened the surface and remained on it in the form of a boundary layer. At the same time, the concentration of the components by volume could change – there is more binder at the contact edge, and more aluminum ammonium perchlorate and catalyst in the middle. When such an enriched paste comes into contact with the heated surface of an electric candle, detonation could occur. The action of the shock wave could destroy the model and be recorded by the pressure sensor. Since the gap between the washers is quite small and is probably smaller than the critical size, the detonation does not penetrate into the depth of the filament, but subsided, turned into deflagration combustion in the supply pipeline, which was observed through the video recording equipment.

Based on what has been described, one more criterion can be deduced when designing rocket engines on paste-like fuel. The concentration of the binder component must be such that, when passing through the entire supply system from the tank to the combustion chamber, the paste is not enriched with an oxidizer to a concentration that can detonate. This requirement can be achieved by introducing lower concentrations, but more effective phlegmatizers, which would prevent the detonation process. The engine start-up system must not

Table

Recipe of pasty fuel

Component	Content, %
Ammonium perchlorate	70.14
Rubber	8.5
Dioctyl sebacinate	5.16
Diethylferracene	0.5
Epoxy resin	0.5
Aluminum powder	15
Cationate	0.2

exceed the allowable values of the pressure jump at the start of the paste combustion in the chamber. The filament block must have a characteristic size smaller than the critical detonation diameter of the paste or its components.

Conclusions. The results of fire tests of a rocket engine on pasty fuel are analyzed. Criterion characteristics are determined. On the basis of experimental studies, another criterion for the performance of a rocket engine on paste-like fuel and its trouble-free operation was developed. This criterion must be taken into account when designing rocket engines.

The results of the experiment were analyzed, the hypothesis about the decrease in the concentration of the polymer binding component in the paste, which passes through the branched surface of the filament, was put forward and substantiated. The speed of the engine element during the explosion was evaluated. It is shown that during explosive combustion in this design of the engine, it is not possible to obtain a pressure value that could ensure the fixed movement parameters due to the large area and, accordingly, mass consumption.

For a more accurate assessment of the results of the emergency experiment, further research should be focused on modeling the flow of the paste through the volume of the filament and determining the change in the concentration of components in it.

Acknowledgements. *The research is partly funded under by program "Support for the development of priority areas of scientific research (CPCE 6541230) for 2023–2024*".

References.

1. Marchenko, V.T., Sazina, N.P., Khorolsky, P.P., & Voznenko, A.A. (2018). A model for calculating the expected costs for the creation of new rocket and space technology, taking into account uncertainty factors. *Technical mechanics*, (2), 30-43. https://doi.org/10.15407/itm2018.02.030.

2. Syutkina-Doronina, S.V. (2017). On the issue of optimization of design parameters and control programs for a rocket object with a solid rocket engine. *Aerospace engineering and technology, 2*(137), 44-59.

3. Meng, Z. (2023). A prescribed time attitude control method based on thrust vector control (TVC) nozzle for solid propulsion satellite. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 237*(8), 1930-1942. https://doi.org/10.1177/09544100221140446.

4. Strelnikov, G.O., Ignatiev, O.D., Pryadko, N.S., Ternova, K.V., & Vasiliv, S.S. (2021). Thoroughly curing by gas flows in rocket engines. *Technical Mechanics*, (2), 60-77. https://doi.org/10.15407/itm2021.02.0608.

5. Ivanchenko, A.M., Bondarenko, S.G., Protsan, Y.V., & Wilson, Sh.A. (2012). Deep Regulation and Reusable Rocket Propulsion Using Premixed Slurry Propellant. *Journal of Propulsion and Power, 28*(5), 869-875. https://doi.org/10.2514/1.B34280.

6. Bulat, P.V. (2014). About the detonation engine. *American Journal of Applied Sciences, 11*(8), 1357-1364. https://doi.org/10.3844/ajassp.2014.1357.1364.

7. Katrenko, M.O., Bondarenko, S.G., Sosnovska, O.V., Zolotko, O.Y., Marchenko, O.L., & Podolchak, S.M. (2018). Prospective directing of scientific achievements at the department of motion production. *Bulletin of the Dniprovsky University. Series: Rocket and space technology, 26*(21), 45-54.

8. Zolotko, O.Y., Zolotko, O.V., Sosnovska, O.V., Aksionov, O.S., & Savchenko, I.S. (2020). Features of the design schemes of engines with pulsed detonation chambers. *Aviation and space engineering and technology, 2*(162), 4-10.

9. Surovtsev, A.B., Kovalenko, K.I., Kuzmenko, N.Ya., & Bondarenko, S.G. (2014). Influence of the nature of surfactants on the rheological characteristics of highly filled pasty compositions based on oligomeric rubber and a dispersed filler. *Bulletin of Dnipropetrovsk University, Series: Chemistry, 4*(22), 76-81. https://doi.org/10.15421/081415.

Горіння й детонація пастоподібного палива ракетних двигунів

С. С. Васильів[1], *Н. С. Прядко*[*1], *С. Г. Бондаренко*[2]

1 – Інститут технічної механіки НАН України і ДКА України, м. Дніпро, Україна

2 – Дніпровський національний університет імені О. Гончара, м. Дніпро, Україна

[*] Автор-кореспондент e-mail: np-2006@ukr.net

Мета. Підтвердження можливості застосування пастоподібного палива на основі перхлорату амонію в ракетному двигуні та виявлення особливостей горіння його при цьому.

Методика. Попередніми експериментальними дослідженнями горіння пастоподібного палива в бомбі постійного тиску визначена швидкість горіння за різних тисків. Була підтверджена стабільність дефлаграційного горіння без переходу в детонаційний режим. При вогневому випробуванні моделі двигуна на пастоподібному паливі стався вибух. Аналіз причин вибуху дозволив висунути гіпотезу щодо збагачення пастоподібного палива перхлоратом амонію, що створило передумови для його детонації. Проведені додаткові експерименти показали зміну режиму горіння при збагаченні пастоподібного палива перхлоратом амонію.

Результати. Теоретичними та експериментальними дослідженнями показана можливість одержання детонаційного палива на основі збагачення пастоподібного палива перхлоратом амонію. Доведено, що за певних умов виробництва пастоподібні палива можуть детонувати, що відкриває новий шлях використання таких палив для ракетних двигунів. Визначені умови переходу режиму горіння пастоподібного палива з дефлаграційного горіння на детонаційне. Проведена оцінка швидкості елементу двигуна при вибуху й показано, що при вибуховому горінні через велику площу і, відповідно, масову витрату не можливо отримати значення тиску, яке могло би забезпечити параметри руху, що зареєстровані в даній конструкції двигуна.

Наукова новизна. Полягає у встановленні ще одного критерію працездатності двигуна при проектуванні його на пастоподібному паливі. Виявлено ефект збагачення пастоподібного палива перхлоратом амонію при його протіканні через систему постачання в момент запуску.

Практична значимість. Наведена інформація дозволяє вдосконалювати конструкцію двигуна на пастоподібному паливі й модернізувати стенд для його випробувань.

Ключові слова: *критичний діаметр детонації, концентрація зв'язуючого філь'єра, пастоподібне ракетне паливо, перхлорат амонію*

The manuscript was submitted 19.03.23.