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GAS FLOW PECULIARITIES IN A SEMI-CLOSED VOLUME DURING THE EXPLOSION OF AN ELONGATED CHARGE OF A CONDENSED EXPLOSIVE SUBSTANCE

Purpose. Confirmation of effect refinement of cord charge detonation during the simultaneous combustion of high-energy materials based on double-base propellants and artillery powders on the walls of a semi-closed volume.

Methodology. To verify the results of previous experimental studies on features of important element of cord detonation engines, in particular the damper, the study used numerical flow simulation in a semi-closed volume according to the Navier-Stokes equations by the finite volume method in the SolidWorks application software package. In the initial area of the engine, the unsteady problem of extended charge detonation along a spiral was considered.

Findings. Based on the detonation feature analysis of energetic materials in a semi-closed volume, the design of a detonation solid-fuel engine was refined and its application scope was set on depending on the starting mass. The energy characteristics of a solid-fuel detonation engine were determined taking into account the gasification process of pentaerythritol tetranitrate and double-base gun powder in different combustion modes. A significant impact of detonation products on the engine body has been revealed, which requires the protective shell using in the design or the removal of an extended charge to a certain distance

Originality. It consists in establishing a significant impact of detonation products on the engine body, which requires modernization of the engine design.

Practical value. The assessment of flow nature of reaction products of high-energy materials allows predicting the consequences of the process and preventing negative results during engine operation process. The determined characteristics and the behavior features of double-base gunpowder combustion products must be taken into account when working with rock, especially during blasting operations and crushing under significant pressure.

Keywords: *cord detonation engine, double-base gun powder, damper, semi-closed volume, extended charge*

Introduction. Explosive materials placed in cord charges have been widely used for mining. Among the explosive materials, the use of high-energy ones based on double-base gun powder and artillery powders is considered for such tasks [1]. This issue becomes even more relevant for demining the territory of Ukraine, which got involved into military operations. Therefore, the disposing problem of high-energy materials, which cannot be used in military operations for various reasons, is an urgent problem. Cord charges are a semi-closed volume filled with explosives. However, if the explosives include high-energy materials based on double-base gun powder rocket fuels and artillery powders, this introduces certain features into the rock crushing process, because they can burn at high pressure without going into detonation. Therefore, it is important to develop an approach to assessing the nature of the reaction product flow under such conditions.

Nowadays, it is necessary to use an explosive composition with high and stable explosive characteristics for developing mineral deposits. Thermal decomposition and combustion catalysts are used to increase the combustion efficiency of oxidizers and fuel systems. The choice of catalysts is made according to the physical and chemical features of the processes. The coal powder addition to explosive mixtures promotes the gas release during thermal decomposition, which, in the absence of air, leads to the formation of soot. This allows you to create gas inclusions, which are necessary for detonation, and soot to catalyze combustion and explosion reactions. A distinctive feature of this composition is the ability to adjust the size of nano- and microparticles, their surface and physical properties due to a change in composition and pyrolysis conditions, which also contributes to lowering the synthesis temperature. Also, a significant difference of the proposed explosive composition including an oxidizer, fuel, and sensitizers is that finely dispersed coal fractions with a high content of volatile components, coal powder, and soot are used to generate gases and increase the explosion efficiency. As the author said (Zakusilo V. R., Zheltonozhko A. A., Boyko L. V., Uzzhina L. N, 2003) polymer-salt compositions based on water-soluble nonionic polymers in the polyvinylpyrrolidone – ammonium heptamolybdate system and other systems are used as catalysts for combustion and explosion processes.

Literature review. Detonation is a rapid process with the thermal energy release on a length comparable to the length of the free molecule path, which is accompanied by a shock wave appearance [2]. From the thermodynamic point of view, such process is close to the adiabatic process that occurs without heat exchange with the external environment at a constant volume. Many works are devoted to the theoretical study of non-stationary gas movement that occurs during explosive processes. In particular, some of them are focused on evaluating such flow parameters in jet engines [2, 3]. However, exact solutions are obtained only for one-dimensional calculation schemes [4, 5].

Deflagration combustion occurs at subsonic speeds, and the heat engine that uses it to create mechanical work is described by the Brayton cycle. Such an engine operates at constant pressure (Fig. 1). Detonation combustion occurs at supersonic speeds, and the engines that can use it operates according to the Humphrey cycle at constant volume [6]. The line AB (Fig. 1) reflects the compression of the fuel mixture to the pressure value at which combustion occurs. The combustion process itself is described by the segment BC, at which the volume changes at constant pressure. After this, expansion to ambient pressure occurs along the line CD. The final process is the exhaust and cooling to the initial temperature and volume (segment DA)

The Humphrey cycle begins in the same way as the Brayton cycle – compression of the fuel mixture on the segment AB. But this does not occur with the help of a compressor as in a turbojet engine, but due to a shock wave. The BC1 line describes the stage of the chemical reaction at a constant volume, since the heat gain occurs directly behind the shock wave. This leads to a pressure increase to point C1. After this, expansion occurs along the C1D1 curve. The final process is the exhaust and cooling process on the segment D1A.

The T-S diagram (Fig. 2) illustrates the increase in temperature during combustion in the Humphrey cycle compared to the Brayton cycle, which reflects an increase in thermodynamic efficiency and specific impulse.

The thermodynamic efficiency of the Brayton cycle under the assumption $\frac{T_A}{T_B} \approx \frac{T_C}{T_D}$ is defined as

$$\eta_B = 1 - \frac{T_A}{T_B}.$$

The thermodynamic efficiency of the Brayton cycle is defined as

$$\eta_X = 1 - \gamma \frac{T_A}{T_B} \left[\frac{\frac{T_{C_1}^{\frac{1}{\gamma}}}{T_B} - 1}{\frac{T_{C_1}}{T_B} - 1} \right].$$

As $\gamma \left[\frac{\frac{T_{C_1}^{\frac{1}{\gamma}}}{T_C} - 1}{\frac{\grave{O}_{C_1}}{T_B} - 1} \right] < 1$, then $\eta_X > \eta_B$.

In addition to the lower entropy, the detonation process is characterized by a lower value of the molar mass μ. The kinetics of chemical reactions works according to a different mechanism, since the process speed is much higher than deflagration combustion one, only those reactions occur whose transit time is not greater than the residence time of the mixture components in the detonation wave. In the well-known formula for the gas outflow rate from a supersonic nozzle, the molar mass is in the denominator, which proves another aspect of the increase, accordingly.

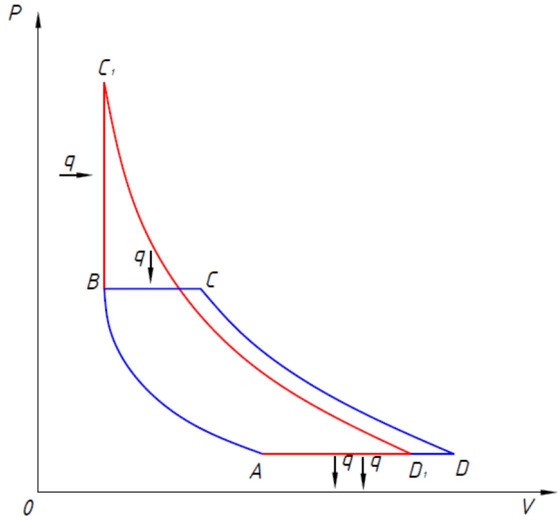

Fig. 1. Comparison of the Brayton and Humphrey cycles on the P–V diagram

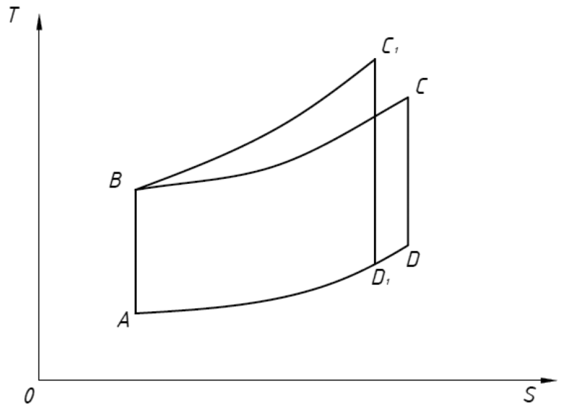

Fig. 2. Comparison of Brayton and Humphrey cycles on the T–S diagram

$$U_a = \sqrt{2 \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{R}{\mu} \cdot T_2 \cdot \left[1 - \left(\frac{p_a}{p_2} \right)^{\frac{\gamma-1}{\gamma}} \right]}.$$

The explosion product expansion in a limited space is a complex non-stationary process that is difficult to study theoretically. A complex picture of shock wave interaction with each other and with the chamber walls is realized here. Approximate individual pulse calculations according to a one-dimensional calculation scheme make it possible to estimate the maximum values of the specific thrust impulse without ambient pressure [7]. According to these estimates, it is in the range of 5,000–9,000 m/s depending on the explosive used as fuel. In real conditions, the specific thrust impulse is lower.

There are many schemes of detonation engines:

The first one is the scheme of a pulsating detonation engine. The V-1 aircraft projectile engine of the Second World War can serve as its prototype [8]. However, instead of combustion in the chamber, detonation is implemented [6]. Probably, this was the very first scheme of a detonation engine, since scientists conducted their first experimental studies of detonation in gases on models made in the form of a tube with one end closed. There are many variants of this scheme, but the engine always operates in a pulsed mode.

The second type is the fuel detonation in stationary shock waves. Fuel is supplied in the supersonic flow of oxidizer emerging from the supersonic nozzle, and a detonation wave is initiated, which moves in the direction opposite to the flow. In experiments, such a detonation process was obtained at parameters that were far from optimal. For the first time these experiments were conducted by J. Nichols with a group of scientists [9]. However, in flight conditions at hypersonic speed, the temperature behind the shock wave is already above 1,000 K. If air with such a temperature level is used for reaction with combustible gases, it will turn out that this detonation engine scheme with a stationary wave is workable and is almost the only one for use in aircraft with a flight speed within $6 < M \leq 17$, since organizing combustion in a supersonic flow is a difficult task and technical solutions are at the stage of experimental research up to nowadays.

The third scheme is built according to the idea of B. V. Voitsekhovsky. He conducted experiments on the implementation of detonation in a continuous spin wave, by analogy with the fuel combustion in a running wave in a round pipe. The combustion chamber, in which it was possible first to obtain such a combustion mode of acetylene-oxygen mixtures, was a flat annular channel. The mixture was supplied through an internal narrow slit gap, and the reaction products were ejected through a wide external gap. The transverse detonation wave propagated inside the channel perpendicular to the flowing mixture, and its speed approached the sound speed in the reaction products. The study of the detonation regime in flat channels was continued by V. V. Mikhailov and M. E. Topchiyan [10]. Theoretically, due to the high thermodynamic efficiency and structural simplicity, detonation engines have an advantage over traditional jet engines based on the Brayton cycle. In addition, during fuel detonation combustion the entropy value of the chemical reaction products is lower than the one for burning fuel in the deflagration mode. In air-jet engines of traditional schemes operating according to the Brayton cycle, the air pressure should be increased to a certain value. And the higher this value, the higher the specific thrust is. However, this process is provided by a complex and, accordingly, expensive manufactured compressor and turbine. With the use of the detonation process, compression and combustion of the fuel mixture is carried out in a detonation wave, so the temperature and pressure in the working process increase, and the engine power is higher than that of gas turbine or rocket engines. Although the amount of energy released during deflagration and detonation combustion of fuel is close, the energy rate released in the detonation mode is several orders of magnitude higher. Therefore, theoretically, detonation engines should be smaller in mass and overall dimensions, as well as faster than traditional engine installations. The operating frequency of a pulsating detonation engine can vary from several tens to several hundred Hz, and in an engine with rotary detonation waves, it reaches tens of kHz.

According to numerous publications that have been made by auto-frames of different countries, it is necessary to notice that the technology of using detonation combustion is still at the stage of experimental research. That is, there are still many problems that need to be solved on the way of creating a workable engine that can be mass produced and used. Since military developments are closed in nature, there is no reason to claim that such engines do not exist.

Research conducted in Ukraine is focused more on the detonation use in applied tasks, for example, in mining engineering and other industries. However, there are almost no publications in the direction of creating air-jet detonation engines. Certain results from research on detonation and rotary detonation engines were obtained at the Institute of Technical Mechanics of the NAS of Ukraine and the SSA of Ukraine. They can be used in Ukrainian developments of air-jet detonation engines.

In detonation rocket engine (DRE) with solid fuel and continuous time-stretched detonation gasification of fuel, fundamentally new, practically unstudied processes occur. The expansion processes and detonation product flow in the chamber with their interaction with the damping charge elements and the chamber walls can't be mathematical described and strongly depend on the design schemes of charge, combustion chamber and engine nozzle.

In the development of DRE with solid fuel, three types of chambers are distinguished: chambers with a Laval nozzle, cylindrical chambers without a nozzle, cylindrical chambers with a supersonic nozzle in the form of a bell.

The processes in the first type chamber are described by integral equations for the gas inlet into the chamber, which is provided by the area of the detonating surface (in this case, the cross-sectional area of the cord), the detonation wave velocity and gas flow consumption from the chamber, which is provided by the critical nozzle section. In this form, the chamber performs the functions of a receiver that is filled and emptied with a nozzle of subsonic and supersonic expansion. To achieve the above-mentioned advantages of the DRE, high pressure is implemented in such combustion chambers, which leads to chamber mass increase and reduces the engine ballistic efficiency.

In a cylindrical combustion chamber, the processes are fundamentally different. The detonation products move from the explosion region towards the exit section at a high supersonic speed, capturing the side flows reflected from the nozzle walls. With a large cylindrical part length of the combustion chamber that is not filled with fuel, jumps of braking (condensation) of combustion product flow may occur in it, which leads to some energy losses of the gas flow and additional heat flows into the chamber wall. This undesirable phenomenon dictates the need to find the optimal length of the combustion chamber and its structural and layout scheme.

The highest thrust impulse was measured in a third type chamber containing an expanding bell nozzle. The task of finding optimal solutions for a chamber and nozzle of this type is complicated and expanded.

The simplest solid-fuel DRE is a semi-closed volume in which the explosive detonation takes place and the detonation products leak into the environment [11]. If a discrete explosive amount is supplied to the combustion chamber, then a pulsating detonation engine can be obtained. The processes in it are much more complicated than in the simplest single-pulse one mentioned above because there is a set of explosive processes interacting with each other and with the chamber walls [6, 12]. The local and integral characteristics of these processes individually and collectively depend on the explosion frequency, on their location area in the chamber, on the activation processes and explosion power, on the combustion chamber composition, input and output devices. If the explosive charge is made with one size that is much larger than the other two (in the cord form), then you can get a long-acting detonation engine, or a corded detonation engine. In such engine with continuous detonation fuel gasification stretched over time, fundamentally new and little-studied processes take place [13, 14]. For example, the processes of expansion and detonation product flow in the chamber with their interaction with the damping charge elements and the chamber walls cannot be mathematically described and strongly depend on the design charge schemes, combustion chamber and engine nozzle.

Schemes of solid-fuel detonation engines can be divided into three types: chambers with a Laval nozzle, cylindrical chambers without a nozzle, chamber with a supersonic nozzle in the form of a diffuser. The processes in the first type chamber are described by integral equations for the gas inflow into the chamber, provided by the detonating surface area (in this case, the cross-sectional cord area) and the detonation wave velocity, and for the gas flow from the chamber, provided by the critical cross-sectional nozzle area. In this form, the camera functions as a receiver filled with detonation products and emptied through a nozzle. High pressure achieved during the condensed system detonation leads to the high energy characteristics on the one hand, and leads to an increase in the chamber mass and reduces the ballistic engine efficiency, on the other one.

The processes are fundamentally different in a cylindrical combustion chamber. Detonation products move at supersonic speed from the explosion area towards the exit cross-section, capturing the lateral flows reflected from the nozzle walls. With a long length of the cylindrical combustion chamber part that is not filled with fuel, compression jumps (inhibition) of the combustion product flow may occur in it, which lead to gas flow energy losses and additional heat flows into the chamber wall. This undesirable phenomenon dictates the need to find the optimal design and detonation chamber layout.

The operation principle of a corded detonation rocket engine consists in the formation of charge reaction products in the detonation process, which imposes certain features on its design. Since the detonation speed is several magnitude orders higher than the burning speed of solid rocket fuels, the corded charge wrapped in spirals burns layer by layer faster than the layer-by-layer burning of conventional solid fuel. Experimental studies of corded DREs were carried out at the test base of Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine (ITM of NASU and SSAU) in the late 80s of the last century. Bench installations were created for these purposes, which made it possible to evaluate their energy characteristics with different explosive types and different geometric cord parameters [4].

The purpose of the work is clarification of cord charge detonation impact during simultaneous combustion of high-energy materials based on ballistic rocket fuels and artillery powders on the walls of a semi-closed volume.

Methods. To achieve the goal, the work analyzes the important element features of cord detonation engines, in particular, the damper. Its new design is proposed. To verify the experimental data, numerical simulation of the flow in a semi-closed volume is used. It is described by the Navier-Stokes equations solved by the finite volume method in the SolidWorks application software package. In the engine entrance the unsteady detonation problem of an elongated charge along a spiral is considered.

Results and discussion. In the above-described engine designs with using explosives, a significant set of thermodynamic parameters is realized. In addition, the associated occurrence of shock waves has an impact on both the process and the structure in which it is organized. The cord detonation engine has the following features:

- due to the high speed of detonation and the critical detonation diameter, which cannot be less than 1 mm, the fuel gives a large mass flow value and, accordingly, thrust (from several tons);
- due to the fact that detonation products have already had a supersonic speed, the engine does not need a subsonic part of the nozzle;
- the engine can be made according to the autophagy scheme, when the detonation of the extreme winding destroys the engine hull (housing) in which the charge is placed;
- the engine can have any ratio of diameter to length. A “flat” engine with a large ratio of diameter to length is characterized by a low specific thrust value, but it can be made without a casing (without hull). For example, a corded charge in the form of a spiral, glued to a rocket

element, which must be removed from it (in the separation process);

- the engine has a high degree of chamber filling;
- due to the high burning speed, the end charge is optimal.

Based on the above facts the application scope of the corded detonation engine can be as follows:

Small-sized engines can serve as impulse engines for trajectory correction or starting engines for aircraft that can withstand significant overloads (10–1,000 g). These ones can be anti-tank missiles, grenade launchers, active-reactive projectiles or other types of weapons;

Engines without body can be used to remove rocket elements separated in flight. They are also characterized by high overload values and short operating time, so their possible application field is also related to military equipment. For example, for the missile fairing removal, separation of combat elements or fictitious targets, etc. [8].

Large engines, weighing from hundreds of kilograms to several tons, can be used for starting accelerators. Space rockets, as well as space vehicles, must withstand higher overloads than thrusters. But the most optimal use of such accelerators is for geophysical and ballistic missiles.

In addition to the determination of the specific impulse, the experiments at ITM of NASU and SSAU are also conducted in order to determine the influence of the geometrical charge parameters on its performance. In order to use the cord in the engine design, it is wound in a spiral and placed in the combustion chamber. Depending on the explosive sensitivity the detonation can be transmitted between adjacent turns placed at a certain distance due to the shock wave that passes through the medium surrounding the charge (for example, through air). This can lead to the detonation of the entire charge at one moment, so these turns must be isolated from each other using a special damper. The size of the critical bending cord radius was determined at which the detonation is attenuated, as well as the distance and materials at which the detonation is not transmitted between adjacent turns [9]. Although some experiments included the use of high-energy materials for dampers, they did not fully provide information about the possibility of their application and energy characteristics. Therefore, it is advisable to continue these studies and consider other material options.

Damper material must be well gasified to ensure high energy characteristics of the engine. For the manufacture of this element, it is advisable to use not only special energy materials, but also solid rocket fuels. The main requirement for such substances is the ability to dampen the detonation wave and at the same time not to detonate but only burn. As such material you can use ballistic rocket propellants (double-base propellant) or types of artillery propellant close to them in terms of chemical composition. The operating pressure in such systems reaches several thousand bars and, at the same time, combustion does not turn into detonation [15]. Fuel mixtures have a higher sensitivity and lower pressure values at which the transition from combustion to detonation can occur, so the use of such energy systems is not considered. A typical composition for making a damper can be RSI-12K double-base gun-powder [16, 17]. Since the speed of detonation in condensed systems varies from 4 to 9 km/s, even a cord diameter of 1–2 mm is enough to obtain large mass flow values and, accordingly, needed thrust. In general, the engine scheme is illustrated in Fig. 1. The explosive *4* is made in the form of a cord with a circular cross-section and is inserted into a special damper *5* with spirals. The spirals are also connected to each other by a detonation cord, so the front spreads along the spiral and gradually moves to the next layer, the next spiral. A detonator *3* is used for initiation. Since the gases have already had a supersonic speed after passing the detonation front along the explosive charge, there is no need for the subsonic part of the Laval nozzle [5]. It is necessary to accelerate the gases using the available energy of detonation products. A nozzle *2* is provided for these purposes. The charge is placed in the engine housing *1*. Since the bending radius of the detonation cord is limited, the void formed in the charge is filled with the charge burnout sensor *6*, which is placed in the pipe *7* and ends with the central body *9*. The sensor allows you to control the operation of the engine by transmitting a signal through the cable *8* to the missile control system. To isolate the charge from external influences, it is covered with a protective membrane *11*. The engine body (housing) is protected from the detonation product effect by a heat-protective coating *10*.

The detonation cord length and the detonation speed determine the operating time. For the task of removing rocket elements, the operation time of the detonation engine can be of the order of 10–4 s. The dimensions of such an engine do not exceed 70 mm (Fig. 4).

For simulation detonation process, the most common form of the state equation for the detonation condensed explosive products is the Jones-Wilkinson-Lee (JWL) equation [15]

$$p = A\left(1-\frac{\omega}{R_1V}\right)e^{-R_1V} + B\left(1-\frac{\omega}{R_2V}\right)e^{-R_2V} + \frac{\omega}{V}\overline{E},$$

where $V = \frac{\rho_0}{\rho} = \frac{\upsilon}{\upsilon_0}$ is relative volume; A, B, C, R_1, R_2, ω are coefficients that are determined empirically; $\overline{E}$ is the internal energy per unit volume.

Like most mathematical models, it has its application limits. To expand them, several models have been developed with refined empirical coefficients. For pentaerythritol tetranitrate (TEN), which is considered as a fuel for an engine, the detonation wave parameters have the following values: $p_{in} = 8.7 \cdot 10^9$ Pa; $D = 5{,}480$ m/s and $T_{in} = 4{,}800$ K at $\rho = 1{,}000$ kg/m^3 [15].

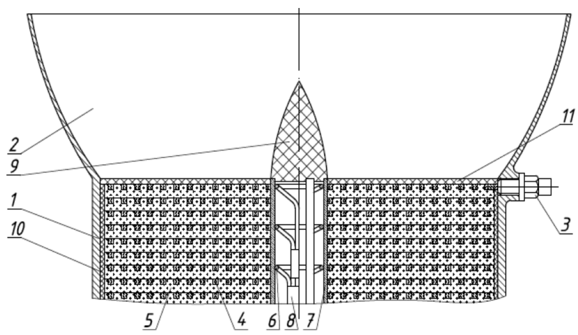

Fig. 3. Scheme of corded detonation rocket engine

Fig. 4. Layout of a corded detonation rocket engine

At the same time, the damper breaks down in the local contact area with the detonating explosive and burns at high pressure. The destruction nature depends on the pressure, which depends on the distance. Therefore, the combustion parameters of the damper material will also depend on the distance. For engineering calculations, the combustion parameters of double-base gunpowder RSI-12K [6, 12], which is considered as a damper material, can be determined by the average pressure. The gas flow in a semi-closed volume is modeled using the Navier-Stokes equations, which in the general case in Cartesian coordinates have the form [18]

$$\frac{\partial U}{\partial t}+\frac{\partial F_1}{\partial x_1}+\frac{\partial F_2}{\partial x_2}+\frac{\partial F_3}{\partial x_3}=0,$$

where

$$F_j=F_j(U,U_{x_1},U_{x_2},U_{x_3}); \quad U=\begin{pmatrix}\rho\\ \rho u_1\\ \rho u_2\\ \rho u_3\\ e\end{pmatrix};$$

$$F_1=\begin{pmatrix}\rho u_1\\ \rho u_1^2+p-\tau_{11}\\ \rho u_1 u_2-\tau_{12}\\ \rho u_1 u_3-\tau_{13}\\ (e+p)u_1-q_1\end{pmatrix}; \quad F_2=\begin{pmatrix}\rho u_2\\ \rho u_1 u_2-\tau_{12}\\ \rho u_2^2+p-\tau_{22}\\ \rho u_2 u_3-\tau_{23}\\ (e+p)u_2-q_2\end{pmatrix};$$

$$F_3=\begin{pmatrix}\rho u_3\\ \rho u_1 u_3-\tau_{13}\\ \rho u_2 u_3-\tau_{23}\\ \rho u_3^2+p-\tau_{33}\\ (e+p)u_3-q_3\end{pmatrix},$$

where $u=(u_1, u_2, u_3)$ is gas velocity vector; t is time; F is external force; p is pressure; ρ is density; e is total energy per unit volume.

The viscous stress tensor components are expressed as a linear derivative combination of the velocity vector components

$$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)+\lambda\delta_{ij}\operatorname{div}u;$$

$$\lambda=\mu'-\frac{2}{3}\mu,$$

where μ is the viscosity coefficient and μ' is the coefficient of the "second viscosity". In the energy conservation equation, the terms q_i have the following form

$$q_i=\sum_{j=1}^{3}\tau_{ij}u_j+k\frac{\partial T}{\partial x_i},$$

where T is the temperature; k is the thermal conductivity coefficient.

To solve the system of equations, the finite volume method is used, which is implemented in the SolidWorks application software package. The essence of the method is to approximate the conservation law in integral form. The physical domain is divided into a computational domain using a difference grid consisting of finite volumes for which the parameters are determined.

Computer simulation is used to study the detonation product flow. At the engine entrance, the non-stationary detonation task of an elongated charge along a spiral is considered. For simplification, damper gasification at high pressures is considered as rapid combustion. The initial parameters of the gas are molar. The time step changes and for the most characteristic pictures, for large value of individual derivatives, it is $1 \cdot 10^{-6}$ s.

Fig. 5 illustrates the pressure distribution on the inner detonation engine surface at the detonation moment of elongated explosive charge. Since the charge is arranged in spirals, the gasification plane is normal to its axis. The logic of the detonation cord combustion suggests that a powerful vortex should be realized in the ring chamber.

However, simulation shows that detonation products flow around the central body and expand into the nozzle. A distance of about 3 diameters is still not enough for the pressure on the nozzle section to equal-

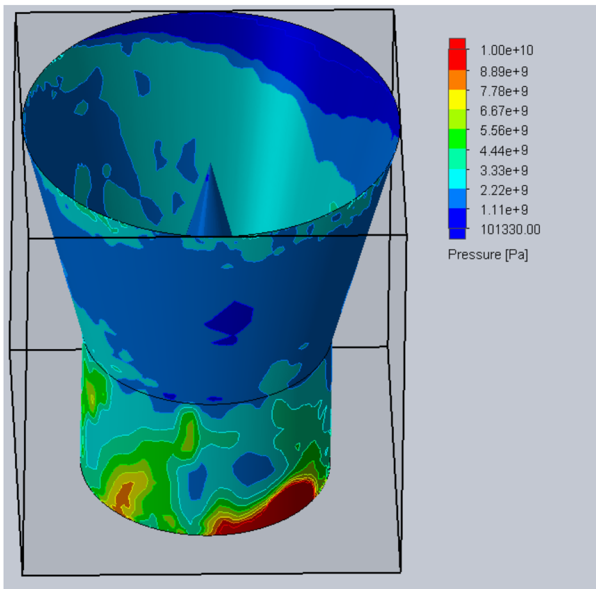

Fig. 5. Pressure distribution on the inner engine surface

ize. Therefore, there is a need to optimize the geometric nozzle parameters for further more efficient gas energy use. The eddy current is evened out to some extent. In the experimental tests conducted in the 80s of the last century, the torque, which has to be created during the vortex flow from the nozzle, is not also recorded. The local pressure value in the contact zone of the charge detonation products reaches 1,010 Pa. This feature requires an additional protective layer, which can reduce the intensity, or the elongate charge distance from the wall of the housing to a distance, at which their pressure drops to a value that the body material can withstand due to the expansion of the detonation products. Despite the small distance between the elongated charge and the central body, the pressure on its surface is much lower than on the body. Therefore, the use of special protective coatings is not required. The energy characteristics of a solid fuel detonation engine with an explosive charge (TEN) content of 9.9 % is 138.9 kN, specific thrust is ~250 s.

Conclusions. Based on the features of the energy material detonation in a semi-closed volume, the detonation solid fuel engine design, which can be attributed to this construction type, was analyzed. Its application spheres are determined depending on the starting mass. Computer flow simulation in a semi-closed volume of an elongated explosive charge is carried out. The energy characteristics of a solid-fuel detonation engine are determined, taking into account the gasification process of TEN and ballistic powder in different combustion modes. A significant detonation product impact on the engine housing was detected, which requires the introduction

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Особливості течії газу в напівзамкнутому об'ємі при вибуху подовженого заряду конденсованої вибухової речовини

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Мета. Уточнення впливу детонації шнурового заряду при одночасному горінні високоенергетичних матеріалів на основі баліститних ракетних палив та артилерійських порохів на стінки напівзамкнутого об'єму.

Методика. Для перевірки результатів попередніх експериментальних робіт щодо особливостей важливих елементів шнурових детонаційних двигунів, зокрема демпферу, у дослідженні було використане чисельне моделювання течії в напівзамкнутому об'ємі за рівняннями Нав'є-Стокса методом скінченних об'ємів у прикладному програмному пакеті SolidWorks. У вихідній області двигуна розглядалась нестаціонарна задача детонації подовженого заряду по спіралі.

Результати. На основі аналізу особливостей детонації енергетичних матеріалів у напівзамкнутому об'ємі уточнена конструкція детонаційного твердопаливного двигуна й визначені сфери його застосування в залежності від стартової маси. Визначені енергетичні характеристики твердопаливного детонаційного двигуна з урахуванням процесу газифікації тетранітрату пентаеритриту й балиститного пороху в різних режимах горіння. Виявлено значний вплив продуктів детонації на корпус двигуна, що потребує введення в конструкцію захисної оболонки або віддалення на певну відстань подовженого заряду.

Наукова новизна. Полягає у встановленні значного впливу продуктів детонації на корпус двигуна, що потребує модернізації конструкції двигуна.

Практична значимість. Проведена оцінка характеру течії продуктів реакції високоенергетичних матеріалів дозволяє передбачати наслідки процесу й запобігати негативним результатам при роботі двигунів. Визначені характеристики й особливості поведінки продуктів горіння балиститного пороху необхідно враховувати також при роботах із гірничою породою, особливо при вибухових роботах, дробленні під значним тиском.

Ключові слова: *шнуровий детонаційний двигун, балиститний порох, демпфер, напівзамкнутий об'єм, продовжений заряд*

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