Лазерний метод дезактивації базується на випаровуванні оксидних плівок під впливом випромінювання. За випарювального механізму лазерне випромінювання повинно за час імпульсу нагріти верхній шар плівки до температури кипіння та випарити його. Він актуальний тому, що у світі зростають вимоги до екологічної безпеки, це дає можливість створення компактної, енергоефективної лазерної установки. На відміну від існуючих лазерних енергоефективних установок, детонаційна лазерна система надасть можливість суттєво впливати та швидко здійснювати дезактивацію забруднених поверхонь радіоактивними ізотопами за рахунок випаровування оксидних плівок під дією випромінювання. Детонаційні технології відносяться до критичних технологій, на основі яких можуть бути реалізовані пульсуючі детонаційні системи, наприклад, пульсуючі детонаційні двигуни, детонаційні лазери, магнітогідродинамічні генератори з детонаційним згоранням палива, системи ініціювання об'ємного вибуху. Впровадження цих систем на озброєнні та військовій техніці може суттєво змінити сферу їх застосування. Середня потужність лазера може перевищувати 100 кВт і вище. При цьому, застосування суміщі, як джерела енергії, робить систему не тільки компактною, але і малою по масі у відношенні до існуючих подібних систем. Довжина хвилі за рахунок формування випромінювання в далекій інфрачервоній області становитиме 10,6 мкм. Тобто, комбіновані силові установки забезпечать не тільки силовий привід і електричне енергозабезпечення машин. Це дозволить створити силові детонаційні установки з частотою періодичного ініціювання не менш, ніж 100 Гц, які будуть працювати на зрідженій суміші і незначним використання кисню в запальною порції

Ключові слова: іскровий розряд, передіонізаціея, струмопровідний канал, лазери, детонація, дезактивація, лазерне випромінювання, напруга

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RATIONALE FOR CREATING DETONATION CO_2 LASER FOR RADIOACTIVE SURFACE DECONTAMINATION

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1. Introduction

The radiation exposure of ionizing radiation sources, which are widely used in the world, is one of the dangerous technogenic factors that can have a negative effect on humans and the environment as a result of destruction. The use of ionizing radiation sources in violation of norms, rules and standards on radiation safety creates the risk of external radiation. These violations can lead to pollution of the environment and intake of radioactive substances into the human body, as evidenced by the accidents at the Chernobyl nuclear power plant (Ukraine) in 1986 and the Fukushima (Japan) nuclear power plant in 2011.

It was supposed to equip the Ukrainian NPP with solid radwaste partitioning and compaction, solid and liquid radwaste incineration, deep evaporation, radioactive oil reclaiming facilities, etc. But these design solutions have not been fully implemented. The lack of processing complexes leads to premature filling of liquid and solid radwaste storage tanks [1].

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Creating a laser that will reduce the power consumption of the detonation initiation system by reducing the discharge energy loss is relevant.

2. Literature review and problem statement

In [2], it is pointed out that the USA, South Africa and Russia developed and implemented methods of laser isotope separation. Laser lidars are widely used to control the radioisotope pollution of the environment. Some of the US and Russian companies use laser systems for NPP equipment disposal.

In Russia, since the early 1990s the SRC RF TRINITI has begun the development of mobile technology complexes on the basis of powerful gas-discharge CO_2 lasers [3]. In the late 1990s, the MLTK-5 and MLTK-50 complexes were developed. The MLTK-5 complex is designed on the basis of the continuous-wave closed-circuit self-sustained discharge CO_2 laser with a power output of 5 kW based on the car chassis. The MLTK-50 complex was created on the basis of the pulsed-periodic electroionization open-circuit CO_2 laser with a power of 50 kW. The equipment was placed on two automobile semi-trailers with the weight of 48 tons.

In the US, from 1970 to 1980, AVLIS (Atomic Vapor Laser Isotope Separation) developed laser systems that evaporate isotopes [4]. This idea died out due to the total capacity and reduction of armaments. With a laser it is possible to ionize atoms of any isotope. A significant drawback is readjustment from one isotope to another.

The US Department of Energy (DOE) proposed to use high-power lasers for the decontamination of nuclear facilities [5]. Between 1992 and 1996, the Ames laboratory within the Ames Laser Decontamination Project achieved results on the development of the 100 W (248 nm) excimer KrF laser and the (1064 nm) Q-switch Nd: YAG laser to study the movement of radioactive oxide on metal surfaces. For the development, the short-range Nd: YAG laser prototype was proposed, its wavelength was (1064 nm), using conventional optical fibers. Other projects were intended for concrete decontamination [6]. Recently, the COIL (Chemical Oxygen Iodine Laser) chemical laser was proposed for the dismantling of nuclear installations [7].

In France, since 1999 experiments with the Nd: YAG laser and excimer laser have been conducted [8]. The Atomic Energy Commission developed and tested the LEXDIN prototype for plexiglass chamber decontamination. Decontamination was performed by the UV laser: LEXDIN prototype, CEA, 1996, which uses the XeCl laser and laser relay units.

In Brazil, there is a growing interest in laser radioactive decontamination of metal surfaces. The main advantages compared with traditional methods are increased safety, waste reduction, secondary waste reduction, reasonable cost. The main mechanism of CO_2 laser purification is ablation [9].

In [10], the preliminary results of decontamination of 241Am-contaminated metal scrap obtained during processing radioactive lightning rods of laser ablation are given. The Nd: YAG nanosecond laser with a power of 300 mJ was used, leaving only a small amount of secondary waste to be treated.

The practical method of considerable reduction of contaminated waste to be stored using coherent laser radiation for removing fixed contamination only from the surface of metal waste is specified in [11]. The single-mode pulsed fiber laser was used to remove fixed contamination from the stainless steel substrate by ablation.

Experimental results of excimer laser decontamination were obtained for various radionuclides (Cs, Co, Eu, etc.), deposition in different conditions (fixed or non-fixed contamination). The laser decontamination prototype consists of the XeCl laser, a fiber bundle for beam transmission, an optical system, a collecting cell with the filter for removing distant particles, computer control of beam cleaning and movement [12].

The paper [13] describes a laser cleaning prototype based on the process of excimer laser ablation. This prototype was tested at nuclear facilities. It mainly consists of the XeCl laser, fiber bundle for beam transmission, optical systems, collecting cells with the filter for removing distant particles, computer control of beam cleaning and movement.

CO_2 lasers have a number of essential shortcomings, namely high energy efficiency requirements for the installation, large dimensions and weight due to cooling systems and centrifugal compressors, low output power and high production costs.

Detonation combustion of fuel in detonation systems eliminates the need for centrifugal compressors to pump the detonation tube with the corresponding reduction of power consumption.

The idea of using laser radiation was proposed in the form of the detonation laser, which showed high efficiency, but the design was expendable [14].

Based on the above, it can be argued that carrying out a study to the develop proposals on the creation of a compact laser system is expedient. It eliminates the need for centrifugal compressors to pump the detonation tube, cooling systems for laser units, which accordingly reduces energy consumption.

The main and unsettled problem today in the practical implementation of pulse detonation systems is associated with the creation of an energy efficient system of periodic detonation initiation.

3. The aim and objectives of the study

The aim of the study is to identify sources of absorption of high-voltage spark discharge energy in the process of direct detonation initiation in gas mixtures and to determine the mechanisms of influence on the discharge process in order to reduce discharge energy losses.

To achieve the aim, the following objectives were set:

– to determine the requirements for the source of direct detonation initiation in pulse detonation systems, which ensure the reduction of discharge energy losses;

– to improve the experimental and calculation technique of the study of the current-voltage characteristic, instantaneous power values, energy released in the spark gap;

– to propose a flowchart of the laser, laser pumping of which is provided by the process of periodic detonation combustion of fuel.

4. Materials and methods of detonation initiation research

4. 1. Mathematical models of spark discharge development

Mathematical models of spark discharge development by S. I. Drabkina and S. I. Braginsky are considered. The

models take into account the deviation of the gas-plasma state in the current-conducting channel from ideal, providing for the expansion of the energy input radius. Under boundary conditions, the presence of a shock wave, whose parameters depend on the amount of energy introduced into the region simulating the spark channel was set in the models. The solution of the problem is carried out in the self-similar approximation. Modeling in the specified formulation is possible only with respect to the non-reacting medium. Absorption or release of energy as a result of chemical reactions. The development of the high-current spark discharge channel is satisfactorily described by the mathematical models outlined in [15]. The author solved the problem of expanding the current-conducting channel by setting the same pressure in the channel section and using the divergent equations of the mass and energy conservation laws taking into account heat transfer. The current pressure p_{ch} in the current-conducting channel depended on the rate of its expansion.

The models of S. I. Drabkina and S. I. Braginsky take into account the deviation of the plasma state in the conducting channel from ideal, providing for the expansion of the energy input radius. Under the boundary conditions, the presence of the shock wave, whose parameters depend on the amount of energy introduced into the region simulating the spark channel was set in the models. The solution of the problem is carried out in the self-similar approximation. Modeling in the specified formulation is possible only with respect to the non-reacting medium. Absorption or release of energy as a result of chemical reactions leads to a change in the thermodynamic state of the medium with the corresponding influence on the shock wave parameters, and the rate of chemical energy release depends on the intensity of the shock wave. Therefore, mathematical models of spark discharge development can not be used to simulate detonation initiation. Today, mathematical models of spark discharge take into account the kinetics of plasma chemical reactions, radiation heat transfer, and so on.

4. 2. Modeling of detonation initiation in the hydrogen-oxygen mixture by the experimental dynamics of energy input

Modeling of detonation initiation in the spark channel was performed, taking into account the expansion of the energy input region and the energy input curve. The transient process in the R L C circuit with a nonlinear active load was simulated [16]. Voltage variation in the gap was determined from the experimental data of Table 1.

Table 1

Voltage variation in the gap, depending on time

Gap voltage U, V	15,000	5,900	3,130	1,885	1,480	1,250	960
Time t, s	0	$3\cdot10^{-8}$	10^{-7}	$3\cdot10^{-7}$	$5\cdot10^{-7}$	$7\cdot10^{-7}$	10^{-6}

Using the calculated current curve, experimental data on the field voltage in the arc column and changes in the current-conducting channel radius, specific power was calculated (Fig. 1).

In relation to the specified discharge circuit, we have the following dynamics of channel development. Support of the shock wave intensity after the termination of energy input is provided by detonation combustion (Fig. 2).

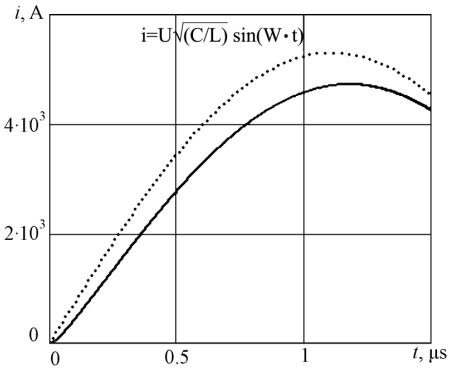


Fig. 1. Specified current curve

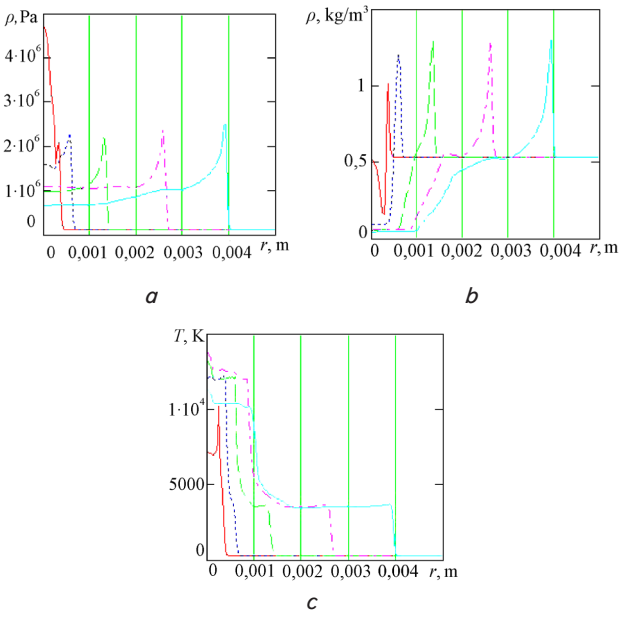


Fig. 2. Distribution over the channel section at timepoints, P_{av}=4.9·10^6 W/cm^3 C_1=0.25 μF, L_1=2 μG, U_1=15 kV: *a* – pressure, *b* – density, *c* – temperature: – 0.1 μs, ····· – 0.2 μs, – – – – 0.5 μs, – · – · – 1 μs, ——— – 1.5 μs

In the above simulation results of detonation initiation by a capacitor with a nominal value C=0.25 μF charged to a voltage $U0$=15 kV and circuit inductance L=2 μG, it is noticeable that at first the radius of the high-pressure region coincides with the radius of the energy input region (t=0.1 μs). Then there is a gap between the shock wave front and the energy input region (channel "shell"), which corresponds to the experimental data [17]. With the development of the spark channel, there is an increase in the distance between the energy input region and the wave front. It is between these areas that there are conditions for the chemical energy release due to hydrogen combustion. The region of chemical energy release is reflected in the appearance of a step on the temperature graph.

Near the axis of the channel, there is a temperature exceeding 10,000 K. At this temperature, hydrogen does not burn, and there are dissociations of molecular hydrogen and oxygen. As a result, temperature growth slows down due to the absorption of some energy in dissociation and ionization processes.

By integrating the energy values, concentrated in components by fixed timepoints, it is possible to estimate the use of the input energy for the combustion process. It was found that for the period up to $t=8\cdot10^{-7}$ s, endothermic reactions caused by absorption of discharge energy as a result of dissociation processes prevail in the discharge (Fig. 3).

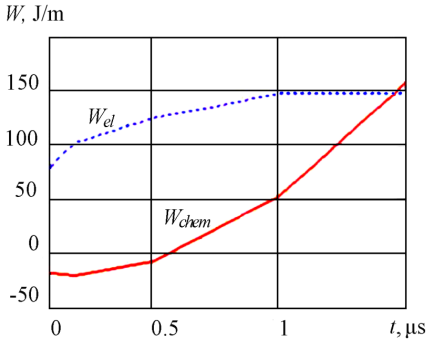
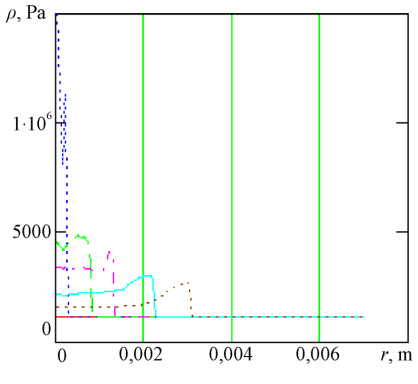
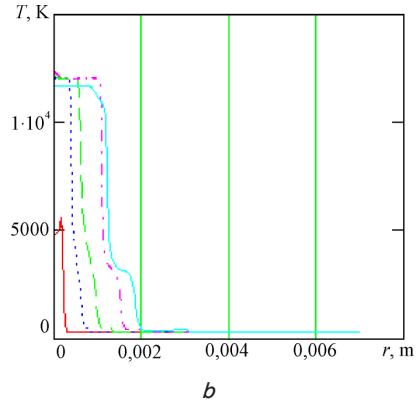


Fig. 3. Change in the amount of electric energy W_{el} ---------- and energy W_{chem}, released (absorbed) during chemical reactions ——

If the inductance of the discharge circuit is increased or the time of energy input is limited, then detonation initiation does not occur C_1=0.25 μF, L_1=12 μG, U_1=15 kV In this case, because of the small size of the chemical energy release area, pressure growth during combustion manages to be compensated by pressure drop due to expansion (Fig. 4).



a



b

Fig. 4. Distribution in the channel section at different timepoints: *a* – pressure: ····· – 0.1 μs, – – – – 0.5 μs, –·–·– 1 μs, —— 2 μs, ····· 3 μs; *b* – temperature: —— – 0.1 μs; ····· – 0.5 μs, – – – – 1 μs, –·–·– 2 μs, —— 3 μs

The study of discharge as a source of direct detonation initiation was carried out with the help of experimental and calculation methods. To calculate the curves of voltage drop in the discharge gap, resistance curves and power curves, the following data were used: initial conditions, circuit parameters, current curves.

As a result of the spark channel development, it was found that the input of energy into the spark channel is carried out not over a fixed radius, there is a voltage drop in the discharge gap, and the current curve deviates from the sinusoid due to attenuation. Therefore, when considering the problem of direct detonation initiation, it is necessary to take into account the time dependence of the energy input into the gas-discharge gap and its redistribution in space.

4. 3. Experimental-calculation technique of the study of the energy input into the spark channel by discharge current oscillograms

The electric circuit includes the electric capacitor and discharge gap. The equivalent electric diagram of this circuit consists of active, inductive and capacitive elements. Capacitance in this circuit is formed by the capacitor own capacity, parasitic capacitances of wires and capacity of the discharge gap until its breakdown. The inductive component is caused by the capacitor own inductance, inductance of the connected wires and inductance of the discharge gap after its breakdown. The active resistance is formed due to the capacitor internal resistance, active resistance of wires and discharge gap. The element with nonlinear characteristics in such a circuit is the discharge gap, which affects the spark discharge in the arc stage due to the nonlinearity of its active resistance. Typically, this circuit can be described as concentrated RLC elements, where active resistance has constant and variable components (Fig. 5).

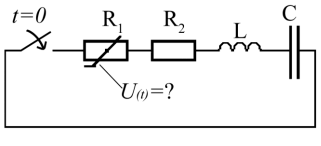


Fig. 5. Equivalent circuit of the capacitor discharge in the discharge gap in the arc stage

The discharge of the circuit was carried out in the short-circuit conditions at the given capacity charging voltage. The active resistance and lumped inductance of the circuit, at which the calculated current curve satisfactorily approximates the measured short-circuit current curve were determined. After that, the spark gap was introduced into the discharge circuit and oscillography of the discharge current curves was carried out.

The value of instantaneous voltage in the discharge gap was calculated by the integral-differential equations, which describe the transient process in the discharge circuit based on Kirchhoff's laws. Each of the equation components in the numerical form looks as follows.

$$u_p = -\left(R_2 \cdot i + L\frac{di}{dt} + \frac{1}{C}\int i \cdot dt\right). \quad (1)$$

The values of current at fixed time intervals Δt were taken from the results of current measurement by a digital oscilloscope, issued in the form of numbers. Accumulation of errors when calculating the values of instantaneous voltage in

the discharge gap can be caused by the summation of errors when calculating the current capacity charging voltage u_c.

$$u_p(t_a)=-\left[\begin{array}{l} R_2\cdot i(t_a)+L\dfrac{i(t_{a+1})-i(t_{a-1})}{2\Delta t}+ \\ +u_c(t_{a-1})-\dfrac{\left[i(t_{a-1})+i(t_a)\Delta t\right]}{2C}\end{array}\right]. \quad (2)$$

The curves of gap resistance and power were determined by the following equations. Calculation of instantaneous gap resistance:

$$r_1(t_a)=-\frac{u_p(t_a)}{i(t_a)}, \quad (3)$$

and calculation of instantaneous power:

$$p(t_a)=u_p(t_a)\cdot i(t_a). \quad (4)$$

To verify the advanced technique, a comparison of the results with the results of direct measurement of the compensated high-voltage divider was made (Fig. 6).

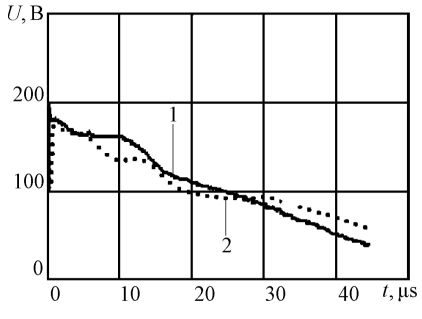


Fig. 6. Comparison of the calculated and experimental curves of voltage in the discharge gap: 1 — voltage measurement by the TEKTRONIX P6015A compensated high-voltage divider, 2 — voltage obtained with the advanced technique of discharge research

The results of the comparison of the resistance curves (curve 1), calculated from the results of direct measurements of the voltage drop in the gap and discharge current, with the resistance curves (curve 2) show a fairly satisfactory coincidence of the experimental and calculated curves, which is reflected in the deviation of the research results by no more than 20 % [18].

4. 4. Experimental study of direct detonation initiation and influence of discharge circuit parameters on discharge characteristics

Spark discharge control in pulse detonation systems is technically feasible in case of voltage drop in the discharge circuit to 2,000 V, that is, in the voltage range where high-speed IGBT transistors operate. For experimental verification of the possibility of direct detonation initiation from the discharge of low-voltage charge capacity, an installation was assembled in accordance with the scheme in Fig. 7. The charge of the capacity C was provided by the CH power supply through the control resistance R. For the discharge at the low voltage of power supply, the discharge gap was closed with a strip of aluminum foil with a thickness of 16±3 μm and a width of 0.5±0.1 mm. The length of the discharge gap was about 10 mm. The moment of detonation initiation was set at the moment of switching on the control unit.

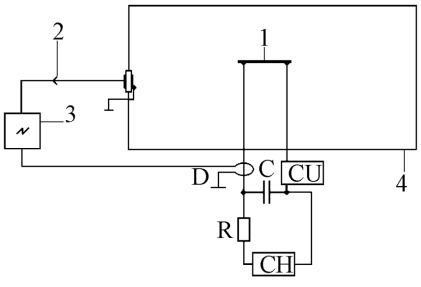
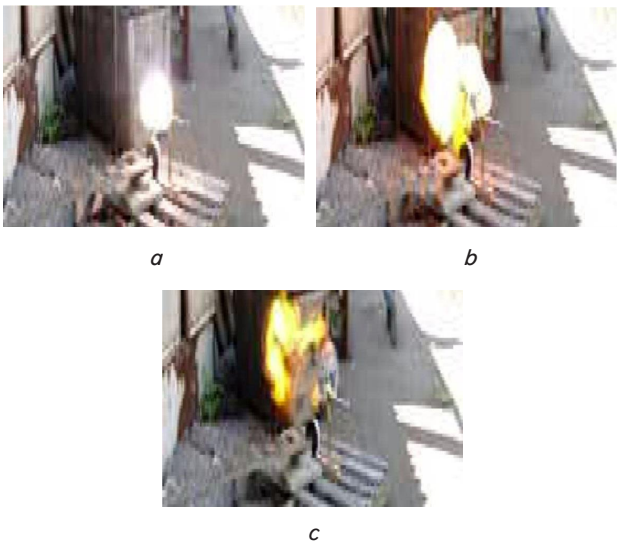


Fig. 7. Scheme of the installation for studying detonation initiation from a low-voltage switch-mode power supply: 1 — foil strip; 2 — piezoelectric sensor; 3 — oscilloscope; 4 — shell; CH — charger (power supply); CU — control unit; R — resistance; C — capacitor D — gas detonation initiation process

The hydrogen-oxygen mixture, close to the stoichiometric composition, was formed in the shell. Measurement of the presence of detonation was carried out using the piezo pressure sensor connected to the oscilloscope. The signal deployment was carried out using the signal received from the non-inductive current sensor. The presence of detonation initiation was determined by the pressure curve recorded by the piezoelectric sensor and by the time the shock wave passed the distance from the initiation point to the sensor. The results of frame-by-frame processing of video footage of shell explosion are given in Fig. 8.



a *b*

c

Fig. 8. Results of frame-by-frame video processing of shell explosion: time interval between the frames — 2 ms: *a* — formation of instant explosion; *b* — slow expansion of detonation products; *c* — explosion epicenter cooling

The experiment used the RIGOL (China) DS1000E oscilloscope with a bandwidth of 20 MHz. The piezo pressure sensor was manufactured on the basis of TsTS-19 piezoceramics. The thickness of aluminum foil was determined by preliminarily measuring the weight of the chosen foil strip, followed by the mass distribution in the area of weighed section. Mass measurement was carried out on the VLR-200 analytical scales of accuracy class 2 accord-

ing to GOST 24104-88. The mass was measured to within 0.1 mg.

The SRI H2-40 hydrogen generator was used to fill the shell with hydrogen. Oxygen filling was carried out by the OnyxAir 2EP oxygen generator, generating oxygen of up to 98 % purity. The hydrogen to oxygen ratio was determined by the volume filling of the shell. This allowed obtaining the hydrogen-oxygen mixture of atmospheric pressure close to the hydrogen to oxygen ratio of 2: 1 (stoichiometric mixture) in the shell. The temperature of the mixture was 300±2 K. The process of detonation initiation was also recorded on the Casio EX-ZR10 ExilimDigitalCamera in the high-speed video filming mode with a frame rate of 480 fps.

On the basis of pulse detonation systems, the option of the detonation laser is proposed. Detonation combustion of fuel, the use of energy of chemical reactions for pumping and the absence of an additional system of pumping the working medium reduce the system's mass and dimensions, increase the efficiency and the working temperature in the medium. It is experimentally proved that due to the decrease in the charge voltage of the capacity (electric field intensity E) in the pre-ionized discharge, an increase in the discharge channel resistance and share of discharge energy released in the gas-discharge gap and near-electrode regions is achieved. For example, in the experiments conducted with a decrease of E= =351 V/cm to E=219 V/cm, this share increased by 5 %. Based on this, requirements for the source of detonation initiation in pulse detonation systems regarding the use of switch-mode power supply with a charge voltage up to 200 V are formed [19].

The detonation laser works as follows [20]. The detonation tube 1 having an opening on one side through the valve system 2 is filled with the hydrogen-oxygen mixture 3 capable of detonation. At the closed end of the tube, with the discharge source 4, detonation initiation 5 in the mixture 3 is carried out. The spread of detonation 6 in the mixture 3 results in "instantaneous" combustion (Fig. 9).

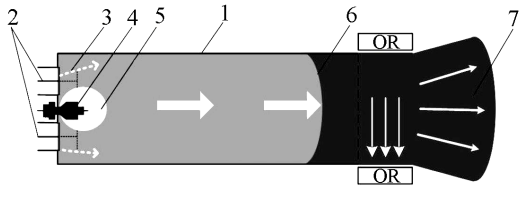


Fig. 9. Flowchart of the detonation laser: OR – optical resonator

The result of detonation combustion is the increase in pressure and temperature

in chemical reaction products, including carbon dioxide CO_2 molecules. The pressure drop formed between the detonation products and the environment results in the supersonic expansion of the detonation products with fast cooling in the area of the optical resonator 7. This creates conditions for the saturation inversion in vibrationally excited CO_2 molecules and provides laser radiation.

At a high frequency of detonation initiation, it becomes acceptable to limit the discharge energy to initiate detonation. So with the energy consumption per one initiation pulse of about 500 J, the total power of the initiation system at a frequency of 100 Hz is 50 kW. This makes detonation lasers energy-efficient with the emergence of technical problems with power supply. It is determined that the energy of the initiation pulse should not exceed 50 J.

Creation and application of the detonation laser with parameters allows decontamination of radioactive objects. Partial cooling of the system occurs due to the periodic operation with filling of the tube with a cold mixture, eliminating the need for large cooling systems. As a result of the research and the obtained data, the initiation system using the hydrogen-oxygen mixture with the following parameters was created:

– energy for single detonation initiation – 50 J;
– detonation initiation frequency – 50 Hz;
– power consumption – 4 kW;
– radiation wavelength – 10.6 microns.

The temperature in the detonation products can exceed 3,000 K, which differs from gas-dynamic CO_2 lasers, where the operating temperature does not exceed 1,400 K, or chemical lasers, where temperature reaches 1,500–1,800 K. In the event of temperature growth, power increases [21].

5. Discussion of the research results of detonation initiation

The sources of spark discharge energy absorption in the process of direct detonation initiation in gas mixtures and mechanisms of influence on the discharge process are determined. The voltage of the switch-mode power supply is reduced to less than 2,000 V, and using IGBT keys, it is possible to terminate the discharge after ¼ of the discharge period.

The calculation model for determining the instantaneous energy values, based on the calculation of the transient process in the *RLC* circuit with the series connected spark gap is improved. In this case, the conducting channel is expanded and the variation of voltage drop in the gas-discharge gap is taken into account. The mathematical model of direct detonation initiation by spark discharge, which takes into account the introduction of energy into the discharge channel that varies in time and space, considering the loss of discharge energy in dissociation and ionization processes is improved.

The flowchart of the laser on the basis of periodic detonation combustion of fuel is proposed. The main and unresolved problem for today in the implementation of pulse detonation systems is the creation of an energy efficient system of periodic detonation initiation. Therefore, the creation of a technology providing an increase in the rate of spark discharge energy conversion into a shock wave belongs to dual-use technologies.

The benefit of the results is the reduction of the total spark discharge energy for initiation to 50 J, which is three times less than in the existing systems.

In order to meet the requirements for increasing the energy efficiency of detonation initiation in pulse detonation systems, it is necessary to ensure spark discharge control. The urgent task is to reduce the power consumption of the detonation initiation system by reducing the loss of discharge energy.

6. Conclusions

1. It is experimentally found that in the capacitive discharge with the pre-ionization by a plasma jet, the share of discharge energy released in the gas-discharge gap is

influenced by the jet outflow direction. In the conditions of experimental research, in case of the plasma jet outflow from the cathode in the direction of the anode, this share exceeded, other things being equal, the share of energy released during the jet outflow from the anode by 5...10 %. On the basis of this, the requirements for the formation of the plasma jet from the cathode are put forward to the source of detonation initiation in pulse detonation systems.

2. Reduction of discharge energy for direct detonation initiation in pulse detonation systems can be achieved by the "forced" reduction of the electric field intensity in the gas-discharge channel, which will result in the limitation of the gas-plasma temperature with the corresponding reduction of energy consumption in dissociation and ionization processes. In the case of limiting the temperature to 4,000...5,000 K, conditions for the predominance of the exothermic reaction with the corresponding additional supply of energy of chemical reactions are fulfilled.

3. On the basis of the obtained results, the requirements for the source of detonation initiation, which ensure the reduction of discharge energy losses by several times compared to the existing systems are formed.

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