Plasma-Wave Initiation of Supersonic Combustion at Low Electric Energy Deposition.

Anatoliy N. Dovbnya[1], Kostyantyn V. Korytchenko[2], Yuriy Ya. Volkolupov[1], Alexander I. Kosoy[1]
[1]National Science Center "Kharkiv Institute of Physics & Technology", Kharkiv, Ukraine
[2]National Technical University "Kharkiv Politechnical Institute", Kharkiv, Ukraine

Corresponding author, K. V. Korytchenko: entropia@rambler.ru

Introduction

There is specification of electric discharge using for an initiation of supersonic combustion at detonation devices working at frequency more than a hundred Hertz. It is caused by need to ignite a combustible mixture at shot time into volume that is much more than a discharge channel by low electric energy deposition in compare to allocating chemical energy. As a rule, acceleration of flame propagation is made by design features of the devices [1, 2]. A combustion velocity of stoichiometric gas mixture is about 0.5 m/s at the atmospheric condition and an initial velocity of the flame propagation is less than 1 m/s [3]. The low velocity lead to a long delay in a velocity increase into detonation tubes. It is known that a flame jet ignition and active chemical radicals excited by a high-voltage impulse discharge let to reduce DDT-time to more than 1.5 times [4, 5]. However, this methods do not allow to form detonation waves at required frequency (more than 200 Hz).

Absence of a detonation initiation is still incomprehensible at a shot-impulse power spark forming of a supersonic expansion of a spark channel when an intensity of the shock wave is enough for its initiation, in spite of wide using of impulse discharge for combustion and detonation initiation, an enormous number of the investigations and a plural of theories explaining of a dynamic development of impulse arc [6, 7]. It is not explained as a physical sense of a time t_0 representing the evacuation time of the region occupied by discharge as how to calculate it that was used in an expression of the critical initiation energy E_* ($E_* \approx \frac{4E_0\tau^2}{\pi^2 t_0^2}$, where E_0 is a minimal energy, τ is a time interval of the energy deposition) presented at [8]. As a result, it is not found a real cause for the detonation failure.

A model of a spark discharge development is presented at this paper up to a moment of a shock wave appearance. The model allows to understand an unlined dependence of the shock wave intensity on the size of the energy input domain.

A plasma-wave method presented at this work allows to obtain supersonic combustion at electrical energy deposition on single initiation up to 100 J due to avoiding of a negative influence of an intensive density decline taking place at the spark channel, creation of conditions for an effective transition of electrons` energy to kinetic energy of ions and molecules by determination of electric-field intensity and obtaining of conditions for the base energy input into a gas-discharge gap by optimisation of a gas-discharge channel length.

Mathematical model of a shock wave formation into a spark and results of the simulation.

The system of governing equations describing 1D reactive flow for cylindrical symmetry is as follows:

$$\frac{\partial \rho}{\partial t} + \upsilon \cdot \frac{\partial \rho}{\partial r} + \rho \cdot \frac{\partial \upsilon}{\partial r} + \frac{\rho \upsilon}{r} = 0\,, \tag{1}$$

$$\frac{\partial \upsilon}{\partial t} + \upsilon \cdot \frac{\partial \upsilon}{\partial r} + \frac{\partial P}{\rho \partial r} = 0\,, \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \cdot \varepsilon + \frac{\rho \cdot \upsilon^2}{2}) + \frac{1}{r}\frac{\partial}{\partial r}\left[r\rho\upsilon\left(\varepsilon + \frac{P}{\rho} + \frac{\upsilon^2}{2} \right)\right] + \frac{\partial (rq)}{r \partial r} = \lambda_{RT} \cdot \sigma \cdot E^2 + Q_{VT} + Q_{eT}\,, \tag{3}$$

where ρ is the density, P is the pressure, υ is velocity, t is the time, r is spatial coordinate, ε is the internal gas energy, E is the longitudinal electric-field intensity, q is the heat flow, $\boldsymbol{\lambda_{RT}}$ is the part of election's energy lost on excitement of onward and rotary energy modes of molecules, σ is the conductivity of the gas channel.
The part of the election's energy losses $\boldsymbol{\lambda_{RT}}$ is set by a function of electron energy distribution.

Numerical values of $\boldsymbol{\lambda_{RT}}$ was taken out of [9] for $N_2 : O_2 = 4 : 1$ mixture by different correlation of E/N, where N is the quantity of molecules into volume unit. The conductivity of an air applied initially to the weak-ionised channel was calculated by the formulae:

$$\sigma(\rho,r) = 1{,}13 \cdot 10^{-16} n_e(r)/\rho, \tag{4}$$

where $n_e(r)$ is the function of electron density distribution at the transverse section channel. The internal gas energy was found out by law:

$$\varepsilon = \frac{1}{\gamma - 1} \cdot \frac{P}{\rho} = c_v T\,, \tag{5}$$

where the γ is the adiabatic factor, c_v is the specific heat.
There are some differences between the model and models of other authors such as using of the uneven function of electron density distribution, admissions that the initial thermodynamic gas parameters are in accordance with environment ones and the same parameters save at the channel border by low disturbing up to a moment of the shock wave appearance, λ_{RT} does not exceed 0.05.
The system of the equations (1) – (5) is blocked and it allows to understand a development of gas-dynamic disturbing into a spark channel up to the moment of the shock wave appearance.
A radius of a cathode spot is about 10^{-6} – 10^{-4} m in accordance with [10]. It gives a base to admit that spot sticking of the discharge channel to the cathode (in compare with diameter of the initial low-conductivity channel) and a process of transverse diffusion are a source of uneven distribution of the current density at the channel section. This is denominated at the spark by the short gap. Thus the initial spark radius has the same size. The function of electron density distribution taken at the calculation had a view

$n_e(r) = n_0 \cdot e^{-1000\,(\frac{r}{r_0})^6}$, where $r_0 = 5 \cdot 10^{-4}$ m (fig. 1)

Maximum electron density taken at the calculation was $n_0 = 10^{16}$ cm^{-3} = const. It was accepted that E = 30 кV/cm = const.

As a result of the modeling, it was received the gas density changes into $\rho_{min} \approx 0.4$ кg/m^3 and $\rho_{max} \approx 1.4$ кg/m^3 limits at the channel section up to $1.6 \cdot 10^{-8}$ s moment and by no more 0.02A of the discharge current (fig. 2). In spite of the rapid density fall occurring for the short time interval a velocity of gas flow does not exceed 120 m/s at its maximum (fig. 3). It has to note a comparative low temperature increase of the gas into the discharge channel which is no more 1600 K (fig. 4).

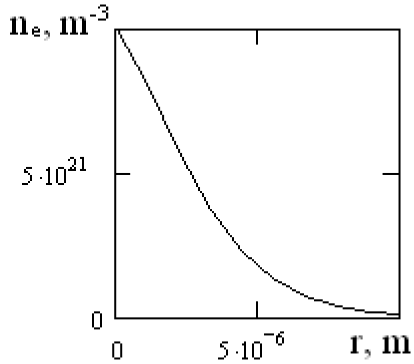


Figure. 1. Distribution of the electron density at the channel section.

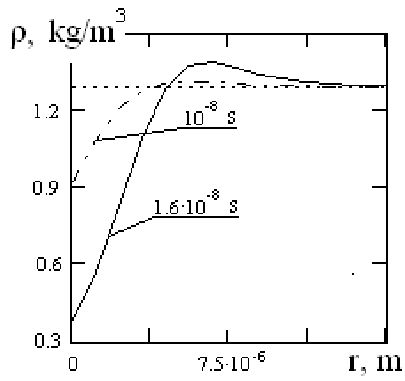


Figure. 2. Distribution of the gas density at the channel section to different time moment.

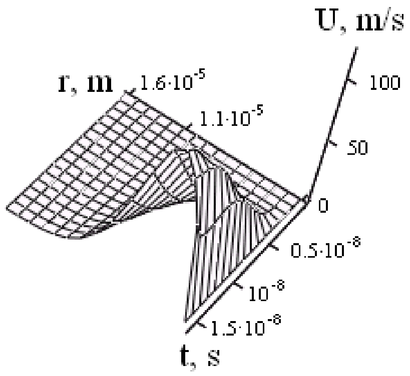


Figure. 3. Velocity of the gas flow at discharge channel.

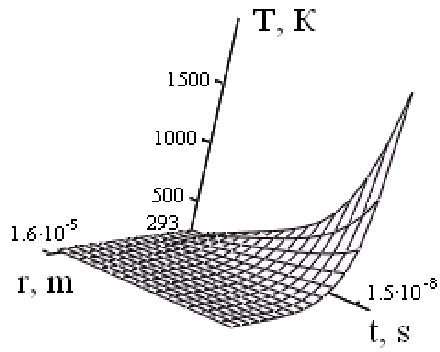


Figure. 4. Dynamic of the gas temperature increasing at the channel section.

Due to the quick gas density fall occurred by the constant electric field it appears the conditions for rapid growing of the taunsend ionisation coefficient. And a part of discharge energy losing on a molecules` ionisation starts to go up at the total energy balance quickly. It leads to a concentration of the discharge current in a field of the lowered gas density.

Based on above said it is considered that the concentration is a main reason for sharp restriction of the shock wave intensity, in spite of the following enormous size of the energy input domain into the spark. So direct initiation of the detonation initiated by the spark appears into weak-detonated mixtures by the energy deposition more than 1 kJ and it does not permit obviously to use the spark for the frequency detonation initiation.

Plasma-wave-system [11]

Further considered is the method to obtain supersonic combustion with small energy electric input due to forming a directional plasma jet and using dynamic properties of gas flows. The above-mentioned task is accomplished by using a device schematically represented in Fig. 5.
The device functions as follows. Cooled air, being under pressure, is supplied from an external source through a conductor 3, along a supply channel 5 and outlets 7 into a cavity 4 of a nonconductor 1. The geometrical dimensions of an output channel 6 and an incident channel 5 with outlets 7 are matched so that in the cavity 4 of the conductor 1 increased pressure forms, with respect to external environment pressure. Further air pressure decrease down to external pressure occurs in the channel 6 as well as behind its cut off. Max velocity of gas flow through the channel 6 can not exceed the critical sound velocity C^* . The velocity of gas distortion spread will vary in the range $Co - C^*$. (Co – sound velocity of stagnated flow). As a result of an electric discharge of a capacity storage through a commutator K in the cavity 4 a part of discharge energy will be directly transformed into kinetic energy, thus causing a pressure increase in the cavity 4, with a compression wave spreading along the channel 6. The incoming gas pressure obstructs gas flow towards channel 5. The velocity of energy conversion from oscillatory into kinetic one being directly proportional to the gas pressure, further pressure increase occurs in the cavity under the influence of relaxation processes. And compression waves with a growing amplitude and a greater velocity will spread along the channel, the gas in it being already partially heated, thus resulting in shock wave formation or high speed plasma jet. Based on the principles of device operation and problems resolved by it, this device is suggested to be called a plasma-wave system (hereinafter PWS).

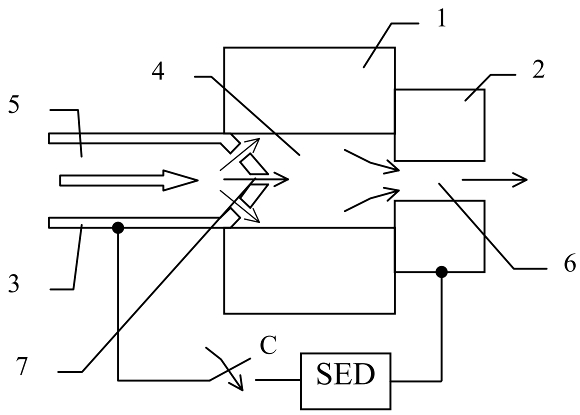


Figure. 5. Plasma-wave system: C – commutator, SED – system of an electric discharge

A change of thermodynamic gas parameters into the cavity during the discharge corresponds roughly to law: P/T=const. Making of initial gas pressure into the cavity which is more then external one lets to reduce max reheat temperature to achieve of a high pressure gradient. Max reheat temperature is determined on the condition that max heated air flow velocity is equal to the critical sound velocity C_{*2},

$$T_H = \frac{C_{*2}^2 \cdot M \cdot (\gamma + 1)}{2\gamma \cdot R} = \frac{D^2 \cdot M (\gamma + 1)}{2\gamma \cdot R}, \tag{6}$$

where M - molar gas mass, kilo-mole; R - universal gas constant. Obviously, due to using of light gas, for example hydrogen, the thermal influence on the PWS material can be reduced. Discharge duration is determined out of plasma wave formation time t

$$t = \frac{2 \cdot l}{C_{01} + C_{02}}, \tag{7}$$

where l – outlet channel length; C_{01}, C_{02} – sound velocity of the stagnated flow under the initial conditions and in the heated electric discharging gas correspondingly.

Particularity of electric discharge organization

The theoretical estimation of conditions was made on the basis of the equation of the electron energy balance to obtain an effective pulse current heating. The expression for a maximal average intensity of an electrical field providing the effective warming up was obtained:

$$\boldsymbol{E} = \frac{1.6 \cdot 10^{-20} \cdot \boldsymbol{n}_0 \cdot \boldsymbol{ln}\wedge}{\boldsymbol{T}} \cdot \sqrt{\frac{1}{\boldsymbol{A}}}, \tag{8}$$

where A – atomic mass of the ion (for example at nitrogen A=28), n_0 – gas density into the cavity, ln^ - C-logarithm, T – required gas temperature.

The analysis of discharge dynamics of an electrical capacitor given high speed energy input has shown impossibility to attain required average intensity of an electrical field in such way. The electrical circuits satisfying to the given requirement therefore were designed. The significant difference in voltage-current characteristics of capacitor discharge (fig. 6) and discharge relating to the circuit are shown (fig. 7). The voltage on the discharge`s gap falls without significant peak fluctuations after breakdown in the second case. Thus the current has practically one halftime of the discharge with duration exceeding this value in 2.5 times in the case of capacitor one. It is necessary to note, that the energy input into the sparks presented on given voltage-current characteristics is identical in the both cases.

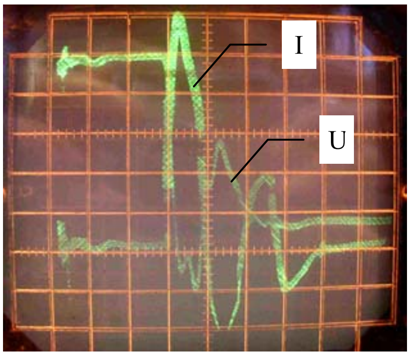


Figure 6 Voltage-current characteristic of a capacitor discharge: The sweep speed is 10 μs/division, the current scale is 500 A/division, and the voltage scale is 500 V/division.

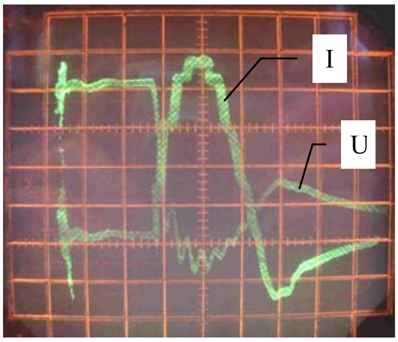


Figure 7 Voltage-current characteristic of pulse-acr discharge: The sweep speed is 10 μs/division, the current scale is 500 A/division, and the voltage scale is 500 V/division.

Experimental setup

The setup was made in accordance the scheme to research PWS parameters (fig. 8). Volume of PWS cavity was $3 \cdot 10^{-7}$ m^3. Pressure of compressed gas supplied from the external source was adjusted in a range of 1÷2.5 MPa. Changing of initial gas pressure into the cavity was made by means of a pressure regulator 3. The value of the pressure was registered by manometer 2 and it was in a range of 0.1÷0.3 MPa. Air consumption of the installation was no more than 7 m^3/h. Creation of plasma was provided with the pulse electrical discharge.

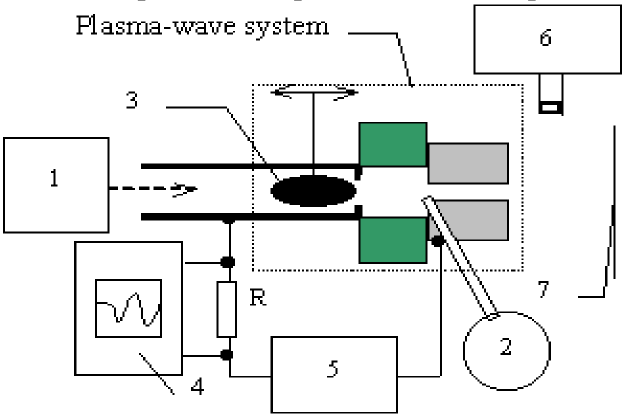


Figure 8 The scheme of the experimental setup: 1- air compressor, 2 – manometer, 3 – regulator of pressure, 4 – oscillograph, 5 – electric discharge system, 6 – photo camera, 7 – obstacle

The air plasma was formed into an air stream. The hydrogen plasma was created during a pulse generation of hydrogen. The capacitor discharge and the discharge of the designed pulse-arc circuit was used. The way of acceleration of oscillatory relaxation was applied to the air plasma. The energy input into the discharge was estimated in accordance with full energy accumulation. A voltage-current characteristic was measured on the discharge`s gap. PWS outlet channel had a different configuration. A length of the channel was from 12 mm up to 20 mm. The emission of a plasma jet occurred into the atmosphere. A portion of acetylene was previously injected at the channel outlet to research the flame velocity. The method of interrupting photography was chosen to measure a velocity of a plasma jet expansion. "СФР" was used as a camera. Exposure time of a film frame was 4 μs. An absolute inaccuracy of the speed measurement was no more than 60 m/s. It was supposed in the analysis that a border of the luminescence area corresponds to the border of the plasma jet distribution. An experimental research of the system parameters has been carried out in a single mode at the present time.

Experimental results

A pulse flow length of luminous area reached more than 100 mm out of the channel edge. An initial pressure into PWS cavity and speed of volumetric energy deposition influences on velocity of the plasma jet expansion significantly. It is caused by influence of these parameters on changing of the pressure into the cavity. Dynamics of velocity changing are shown for the forward plasma front based on air plasma by the initial pressure into the cavity corresponding to 3 atm and 1 atm (fig. 9).

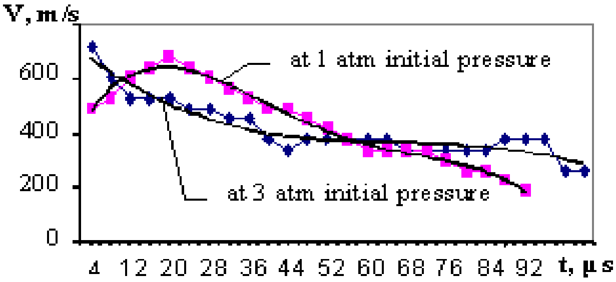


Figure 9. Speed of the forward air-plasma front obtained at different pressure into the cavity

Reduction of time of the oscillatory relaxation allows to increase the velocity of the air plasma expansion initially (fig. 10).

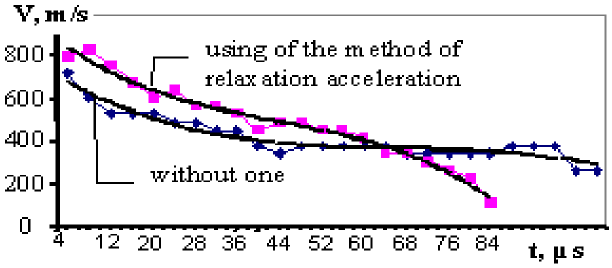


Figure 10. Speed of the forward air-plasma front

The average intensity of an electrical field predetermines process of plasma jet formation. The luminescence area does not have a formed shape (fig. 11) if the field is relatively strong (more than 2 kV/cm). It has been supposed that this area is result of the bombardment of an electron flow provoking a chaotic luminescence into the environment.

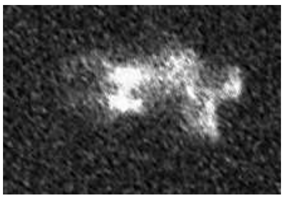


Figure 11. Form of air-plasma jet at the strong electrical field

The invariant shape is formed at the weak field (fig. 12). It has been suggested that the jet formation is predicted by thermodynamic processes in this case.

Figure 12. Form of air-plasma jet at the weak electrical field

Use of the pulse hydrogen generator has allowed to obtain deduction of high speed of the plasma jet spreading during more than 80 μs at decrease of the energy input from 100 J up to 40 J. A fall of the jet speed occurs quicker with reference to the air plasma than to the hydrogen one at reduction of the energy deposition (fig. 13). A rise of the initial pressure and use of the generator of hydrogen allows to attain the jet diameter more than 20 mm (fig. 14).

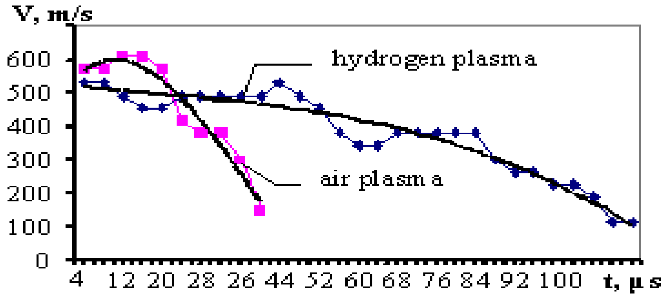


Figure 13. Speed of the forward plasma front by energy input about 40 J.

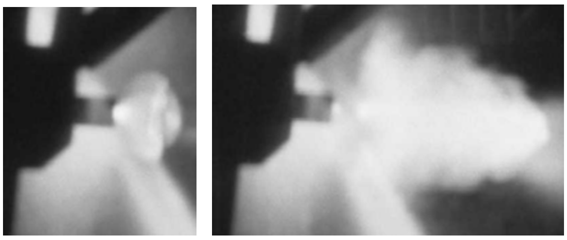


Figure 14. Images of the hydrogen plasma jet propagation into an air after 24 μs and 108 μs accordingly.

The radial velocity of combustion was more than 450 m/s after 24 μs at the acetylene-air environment (fig. 15).
Due to changing average intensity of the field the different ways of an ignition of the acetylene-air mixture were observed. The volumetric ignition – it was observed in a condition of volumetric bombardment of the fuel mixture by a dense flow of electrons or photons, that resulted in reduction of the period of an ignition delay and explosive burning of the mixture then. The shock ignition – there was in case of fast increase in speed of the plasma jet propagation with formation of an intensive shock wave. The volumetric - shock ignition – it was a combination of the first and second ways. In this case requirements to the speed of a pulse plasma flow were reduced. It has been found out that the specified ways of combustion initiation depend on dynamics of an electrical energy input.

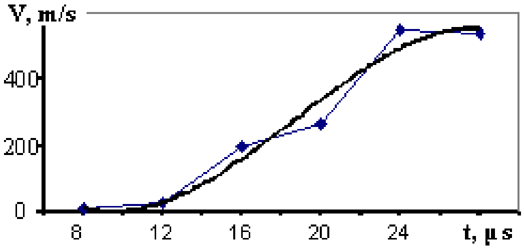
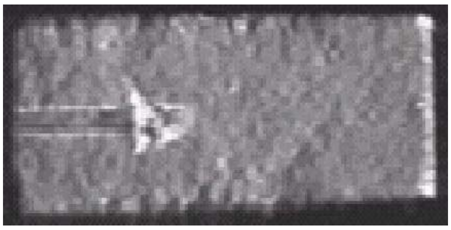


Figure 15. Radial velocity of combustion

It should be noted there is big deference to an ignition delay got at the plasma-jet ignition and high-temperature jet one formed by preliminary gas-mixture combustion into half-restricted volume. As it is visible on the dynamics of flame propagation, the plasma jet initiates process of burning at the jet outlet immediately (fig. 14). According to results of other authors, for example [4], the high-temperature jet ignites after the significant delay indicated by initial spot of flame spreading that is located on a large distance out of the outlet (fig. 16). It can be explained due to presence of a vast quantity of chemical-active radicals into the plasma jet.



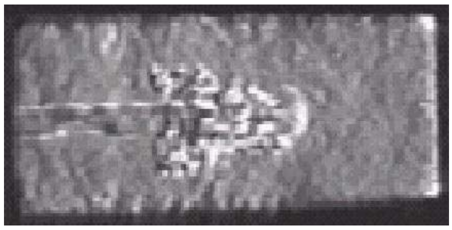


Figure. 16. Images of the high-temperature jet ignition [4].

The application of PWS will allow to reduce time DDT-transition and considerably to decrease a length of a transitive part of a detonation tube.

Prospects of PWS application

The authors are studying possibility to create a power impulse gas-dynamic laser (Tab.1) incorporating new technical solutions (fig. 17). It is for the first time suggested to use separation of detonation products and air at the account of drop-and-liquid fuel torch jet detonation in the process of their development in air environment, thus obtaining inversion of gas molecules oscillation level population in the environment of increased density.

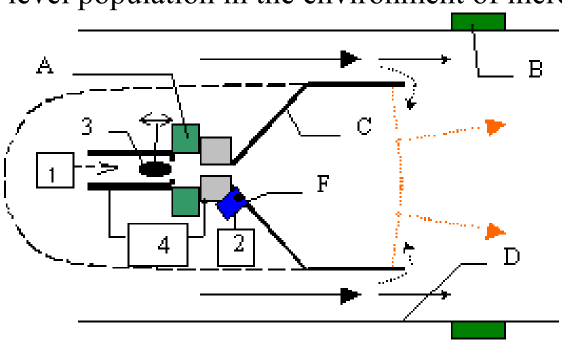


Figure 17. The structural diagram of a gas-dynamic DC pulse detonation combustion laser (or air-get engine): A - plasma-wave system, B – optical resonator, C – detonation chamber, D –

nozzle, F – fuel supply system, 1- air compressor, 2 – fuel supply, 3 – reductor of pressure into the cavity of PWS, 4 - the circuit of pulse-arc discharge

Tab. 1 The expected laser parameters (for the detonation chamber volume of 10^{-3} m^3)

chemical energy source	average power (for 1% efficiency)	max working frequency	emission wavelength	working frequency range
kerosene	3.7 kW	200 Hz	10.6 μm	0 – 200 Hz

There is an ability of a practical realisation of a system for breaching a lane in a minefield containing pressure sensitive mines. A particularity of the way is based on using of a thermal smoke equipment of armoured vehicles (fig. 18). For example, the vehicle 1 equipped an plow is moving across a minefield 2 forming a diesel-air mixture 3 behind its. Than the mines will de damage due to an initiation of a detonation 5 into the mixture. Means 4 based on evaporation of diesel fuel into a stream of hot exhausting gas use for creation of smoke curtain. There are a lot of vehicles supplied the means.
There is technical difficulty of the way realisation due to necessary of creation of a device to initiate a volume explosive at frequency mode. As the detonable mixture is based on diesel-air mixture, it has a high size of detonation cells λ equaled about 10 cm [12]. It is famous that there is a successful detonation transition out of a confined volume to an unconfined one if a condition connected with a geometrical size of a detonation tube is carried out. So a diameter of the tube must be $d >> 13\lambda$ (at the round-section tube) or one of a side should be a height equaled $h >> 10\lambda$ (at the rectangular-section tube). As a result it has to have the tube diameter about 1.3 m to initiate the detonation at the diesel-air mixture formed in unconfined volume. A length of DDT-process happening by the same tube diameter is more 10 m. Thence there is need to use special action to achieve the significant acceleration of DDT-process at the detonation tube.

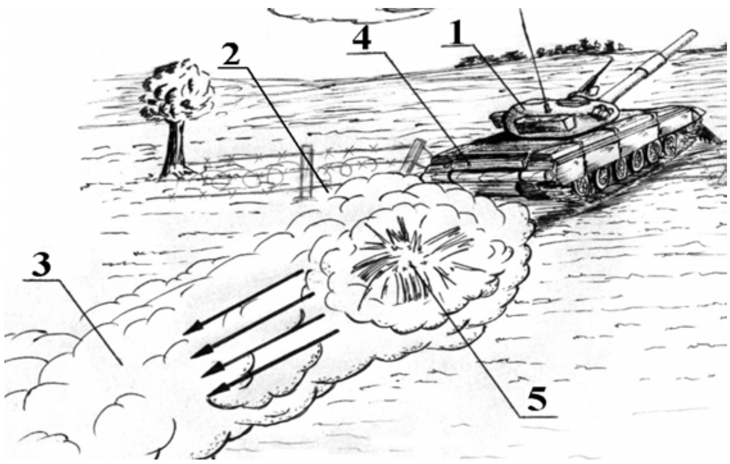


Figure. 18. Minefield clearing by the tank thermal-smoke equipment.

Conclusion

Results of the experimental investigation confirm the correctness of a theoretical predictable way of reducing an intensity of electric field in the arc discharge to obtain an effective and quick efficient of transforming the electric energy to kinetic molecules` energy. It is a perspective manner using the impulse hydrogen generator to get a velocity of forward front spreading of impulse plasma jet more than 350 m/s during 100 μs by decreasing of the electric energy losses to 40 J. The results of the ignition time delay and the velocity dynamics of the jet propagation allow to think about the plasma-wave system application at an device of impulse initiation of high speed burning. It can extend the sphere of detonation using.

Reference

1. Vasil`ev A.A. Optimization of DDT accelerators // International Colloquium on Advances in Confined Detonations : Proceeding. – 2-5 Jule, 2002. - Moscow, Russia, 2002. – P.31-35.
2. Smirnov N., Nikitin V., Kulchitsky A. Nonequilibrium effects in gaseous and heterogeneous detonations // International Colloquium on Advances in Confined Detonations : Proceeding. – 2-5 Jule, 2002. - Moscow, Russia, 2002. – P.139-143.
3. Baum F., Stanukovich K., Shehter B. Physics of explosion. – Moscow, 1959. – 800p.
4. Motoi Suetake, Naomasa Uchida, Koichi Hayashi Experimental and numerical analysis of jet ignition // International Colloquium on the Dynamics of Explosions and Reactive Systems – 1999. – paper № 226.
5. Zhukov V.P., Sechenov V.A., Starikovskii A.Yu. Ignition delay times in lean n-hexane-air mixture at high pressure // Combustion and Flame. – 2004. – Vol.136. – P. 257-259.
6. Aleksandrov N. L., Bazelyan E. M. Temperature and density effects on the properties of a long positive streamer in air // J. Phys. D: Appl. Phys. - 1996. - V 29. –P.2873–2880.
7. Zaepffel C., Hong D., Menn E.Le., Bauchire J.M. Investigation of an electrical discharge for combustion ignition mechanism study // XV International conference on gas discharge and their application, Proceeding. – Sept. 5-10, 2004. - Toulouse, France, 2004. – P.969-972.
8. Levin V., Markov V., Osinkin S., Zhuravskaya T. Initiation of gas detonation by means of electrical discharge // International Symposium on Combustion and Atmospheric Pollution: Proceeding. – 8-11 Jule, 2003. – St. Petersburg, Russia , 2002. – P.290-293.
9. Alecsandrov N., Vysikaylo F., Islamov R. Function of electon distribution at N_2 : O_2=4:1 mixture// Physics of high temperature. – 1981. - V. 19. - P. 22-27.
10. Rayzer Yu. Physics of gas discharge. – Moscow: Nauka, 1992. – 592p.
11. K. Korytchenko, V. Chumacov, M. Ostrizhnoj, M. Krasnogolovets. 2002. Ignition device. Patent of Ukraine No. 47097A, H01T13/00
12. Kees van Wingerden, Dag Bjerketvedt, Jan Road Bakke Detonation in pipe and in the open // http://www.safetynet.de/Publications/articles/CMRNov99.pdf