Violent Deflagration by Impulse Thermal Plasma Jet

Kostyantyn V. Korytchenko[1]
Alexander I. Kosoj[2], Oleg V. Stahovskiy[1], Alexander A. Pleshkov[3], Alexander G. Smorodskiy[4], Sergey M. Shkirida[2], Vadim S. Dyomin[2]

[1]Kharkiv Institute of Armoured Forces by National Technical University “KhPI”,
192 Poltavsky Shlayh Street, Kharkiv, 61034, Ukraine

[2]National Science Center “Kharkiv Institute of Physics & Technology”,
1 Akademicheskaya Street, Kharkiv, 61108, Ukraine

[3]National Aerospace University "Kharkov Aviation Institute"
KhAI, 17 Chkalov Street, Kharkov, 61070, Ukraine

[4]Military Prosecuting Magistracy of Kharkiv Garrison
36 Rydnev Square, Kharkiv, 61050, Ukraine

1 Introduction

Jet ignition is considered as an acceleration method of deflagration-to-detonation transition (DDT) into a detonation tube. There are two types of the igniters based on flame and plasma jets. Experimental results, for example in a work [1, 2], show that flame jet ignition allows significantly to cut DDT time. Making the result estimation it is possible to calculate a speed of the jet spreading and a distance out of an edge of the jet nozzle where an ignition appears. As a rule, the speed does not exceed a sound one and the distance is equaled 3÷8 diameter of the nozzle. It is famous that gas of subsonic jet start to mix with surrounding one from the distance said above. Due to an investigation of a flame-jet ignition made in work [2], it was found out that there is the strong dependence of the flame re-ignition delay on the orifice diameter due to influence on characteristic mixing time depending on vortex structure. An influence of geometrical size of the plasma igniter on combustion process was presented in work [3]. The authors note that the combustion is effectively enhanced when the plasma jet igniter has a large cavity volume. Such influence can be forced by increasing of time of the jet flowing. Thus, the DDT acceleration by the jet ignition is provided with formation of vortex zones leading to intensive mixing of a hot jet gas with cold non-combusted one.

It is known the large-scale vortex structure takes place by enormous Reynolds number. It is necessary to rise the nozzle diameter and (or) to increase the speed of the jet spreading for obtaining such effect. So, it needs to realize quick and effective gas heating into semi-restricted volume to form a high-speed plasma jet. A small part of electric energy deposited from high-voltage capacitor discharge transforms to gas heating during the arcing. So, correlation the experimental and theoretical dates of shock-wave intensity (by overpressure in 0,1÷0,003 times) and energy input into discharge cannel was made in work [4]. The good agreement takes place by a suggestion that 1/6 part of the stored capacitor energy loses on shock wave formation. A research of discharge circuit efficiency was made in work [5] via measurement of shock wave impulse. It was found out that the efficiency decreases if the stored energy rises. “An absolute efficiency value is equaled 4,5 % by 0.5 J of the energy input and the value falls to 1 % by 400 J.” Efficiency comparison of plasma igniters having different lengths and diameters of the discharge volumes that was done in condition of equaled energy deposition shows that increasing of the length and decreasing of the diameter lead to rising of ignition efficiency [3]. It can be caused by improving of the energy transforming that creates a condition for high-speed jet expansion. Thus, a conclusion mentioned in work [6] about advantages of flame-jet ignition in comparison with plasma-jet one is reasonable for plasma igniters which use low-efficiency systems of an electric discharge.

The aim of this work is to found out new ways allowing a rise of efficiency of the heating to accelerate DDT process.

Correspondence to: entropia@rambler.ru

2 Influence of pulse arc driving on dynamic of gas-discharge jet spreading

Arc driving is a peculiarity of the source. The efficiency of pulse transformation from electric energy to thermal gas one is increased due to driving of the arc. The discharge process is influenced by changing of a voltage supplied to the discharge gap:

The way affecting balance of energy deposition:

$$E\downarrow,\ T_e\downarrow,\ R_\kappa\uparrow(R_\kappa \sim 1/\sigma_\kappa,\ \sigma_\kappa \sim T_e^{3/2}):\ R_\kappa >> R_a.$$

The conductivity σ_κ of highly ionized plasma is in direct proportion to the electron temperature T_e: $\sigma_\kappa \sim T_e^{3/2}$. The resistance R_κ of a discharge cannel increases by decreasing T_e because $R_\kappa \sim 1/\sigma_\kappa$. Hence, there is aroused the ability to vary the channel resistance "by force" affecting T_e by changing of electric-field strength E in discharge gap using external voltage. Thus, the primary energy input is attained in the discharge gap if the condition $R_\kappa >> R_a$ is fulfilled, where R_a is the resistance of external electric circuit.

A way of rising of heating efficiency:

$$E\downarrow,\ T_e\downarrow,\ \delta_{ei}\uparrow(\delta_{ei} \sim 1/T_e^2),\ \nu_m\uparrow(\nu_m = NU\delta_{tr} + n_eU\delta_{ei}).$$

Relaxation time between the electron temperature and the temperature of ions, atoms and molecules is basically affected by frequency ν_m of elastic collisions at pulse arcs: $\nu_m = NU\delta_{tr} + n_eU\delta_{ei}$, where N is the density of atoms and molecules, U is a velocity of elastic particles, n_e is an electron density, δ_{tr} and δ_{ei} are cross-sections of elastic collisions of electrons with atoms (molecules) and ions accordingly. There is possibility to increase significantly the frequency by changing the cross-section of electron-ion elastic collisions because $\delta_{ei} \sim 1/T_e^2$ by changing of the voltage supplied to the gap.

A plasma-wave system was used to form a pulse thermal plasma jet (fig. 1). A schematic and an operation principle of the system are described in paper [7]. Air or hydrogen-enriched mixtures were taken as a discharge medium. An ignition process was investigated either in conditions of oncoming interaction of air plasma jet with acetylene jet or in conditions of spreading of hydrogen-enriched plasma jet into air environment. "SFR" was used as a camera to register dynamic of plasma-jet spreading and an ignition process. Average electric-field intensity of arcing and an initial pressure into the discharge cavity were changed during experimental researches. The acceleration method of oscillation relaxation was applied to the air plasma. Hydrogen enrichment of the discharge medium was done during the arcing. An electrical energy deposition was up to 100 J to form a plasma jet.

Dynamic of the hydrogen-enriched jet development is shown (fig. 2). A light background of the images is caused by repeated photographing of residual lighting due to a delay in closing of "SFR" curtain. A diameter of PWS outlet was about 2.5 mm. An intensive transverse extension of the jet was observed beyond an edge of the nozzle at a distance about 5 mm as it is visible on the images. Photographing of the impulse air plasma jet shows resemblance of expansion into the environment to the hydrogen-enriched jet. A firm breakup was observed into the jet lighting. Such jet expansion promotes to intensify the ignition near to the jet exhaust. The combustion took place during the jet spreading too. More over, a rise of the initial pressure and use of the generator of hydrogen allows attaining the large-scale vortex structure.

The investigation of influence of the average electric-field intensity during the arcing on a velocity of the plasma jet spreading confirms in necessary to program the discharge evolution. It is visible that plasma jet created in condition of voltage reducing has more waste expansion than another one (fig. 3). The energy input was equaled of 100 J in both cases.

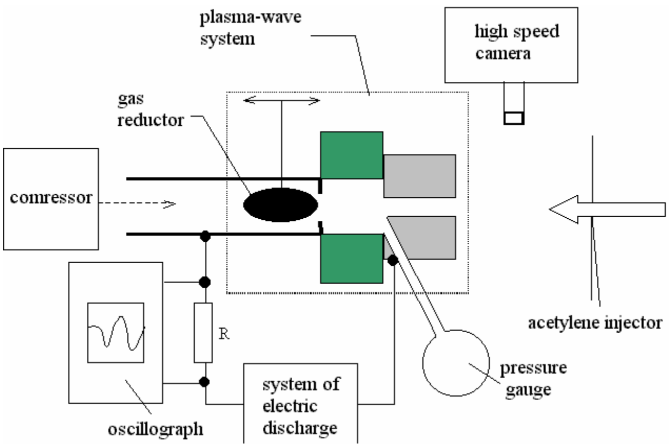


Figure 1 Schematic of the experimental setup

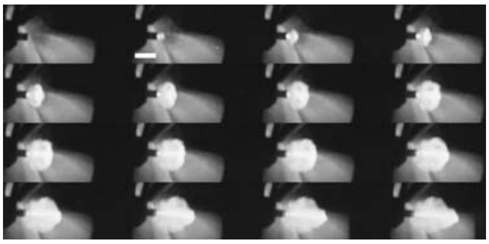
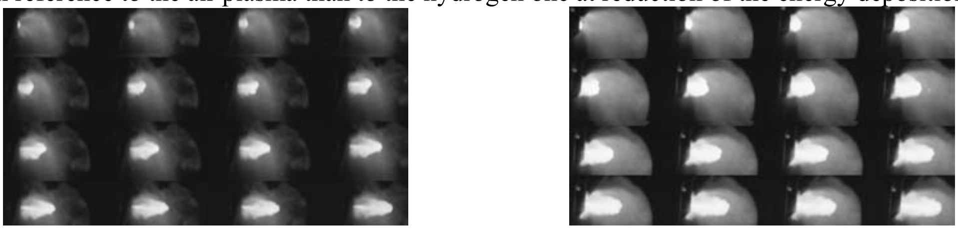


Figure 2 Images of development of the hydrogen-enriched plasma jet into the air environment. Exposure time of a film frame was 8 μs. A length of the line shown on second frame is 20 mm

An absolute inaccuracy of an estimation of the average velocity was no more 30 m/s in these cases. Due to a time analyze of velocity dynamics of the jet development and taking into account duration of the current heating it has been found that an increase in efficiency of the heating allows to rise a velocity of the jet injection. The outflow was determined by relaxation process into the discharge cannel after an expansion time of 40 μs at the experiment. It led to equalization of the velocity of the jet spreading then. There was the same tendency of influence of the field intensity when an air plasma jet was forming. But application of an acceleration method of oscillatory relaxation influences on the air jet velocity. A velocity of a forward front of the air plasma jet corresponded to the velocity gotten in condition of the optimal electric field intensity into impulse arc when the real intensity was twice the optimal one but the acceleration method was used.

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. 4).



a b

Figure 3 Images of development of the hydrogen-enriched plasma jet into the air environment. Exposure time of a film frame was 8 μs. Initial voltages from the discharge system were equalled 16 kV (a) and 900 V (b)

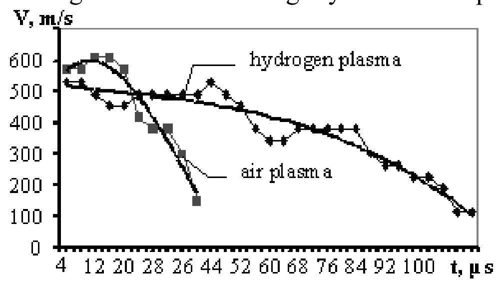


Figure 4 Speed of the forward plasma front by energy input about 40 J

3 Experimental investigation of flame acceleration

The schematics of two experimental setups are presented (fig. 5, 6). The tube was 73 mm in inner diameter and 405 mm long. A series of experiments were carried out at atmospheric initial conditions using stoichiometric acetylene-air mixture or mixture of propane-butane (2/3 mass correlation) with air. Three types of igniters were used such as low energy spark plug, thermal plasma jet source and pulse driven arc igniter. Pressure gauges were used to measure both the pressure wave velocity and pressure profiles. Representative wave profiles recorded by the arc ignition into acetylene-air mixture are shown in fig. 7.

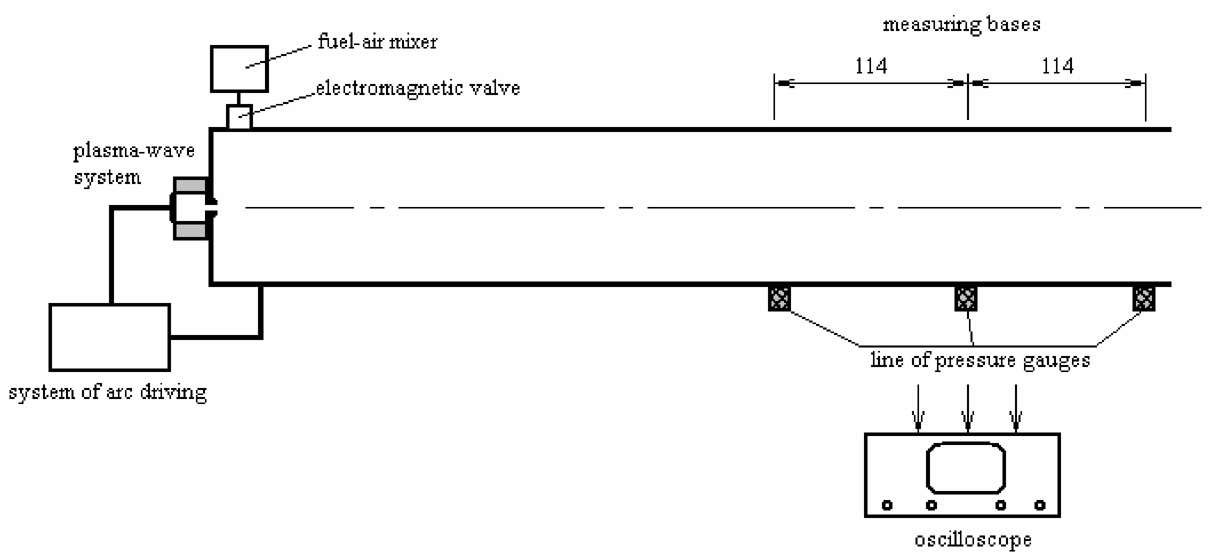


Figure 5 Experimental setup with plasma-jet igniter

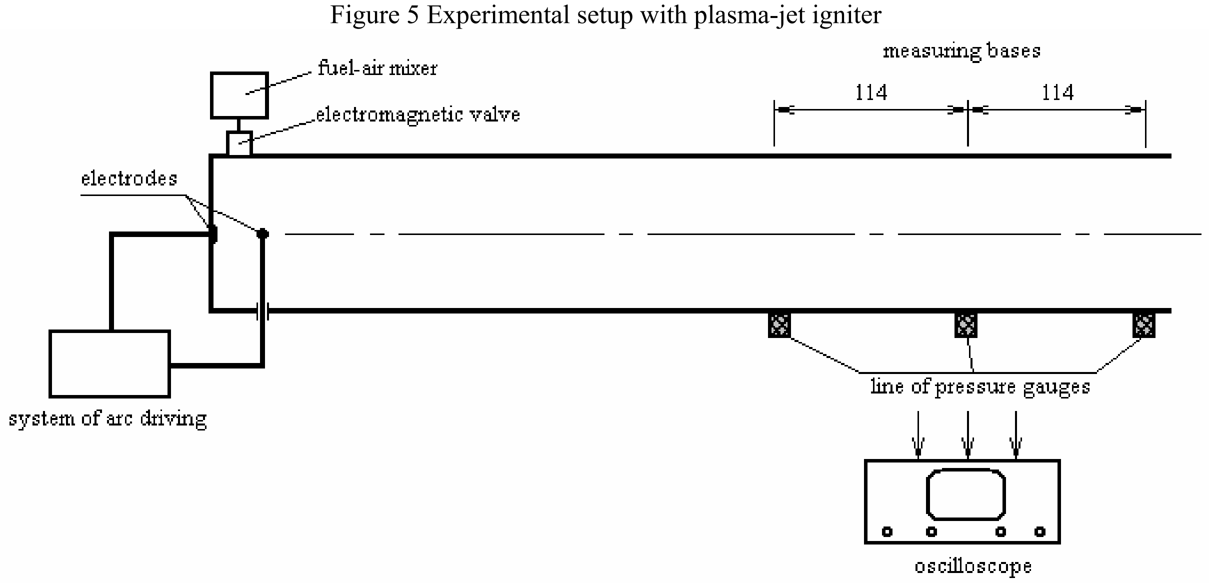


Figure 6 Experimental setup with pulse driven arc igniter

It was obtained that the wave velocity did not exceed 95 m/s into the acetylene-air mixture by low energy ignition (up to 1 J). Comparison of the wave velocity obtained by the plasma jet and pulse arc has shown that the plasma jet igniter accelerates the flame front twice quicker than the arc one by similar driving conditions and energy deposition (up to 100 J). So, the wave velocity achieved 500 m/s by jet igniter and the velocity was up to 305 m/s by arc one. It can be explained more effective flame turbulence by plasma jet. The velocity of the pressure wave generated by the jet ignition was up to 50 m/s into the mixture of propane-butane with air.

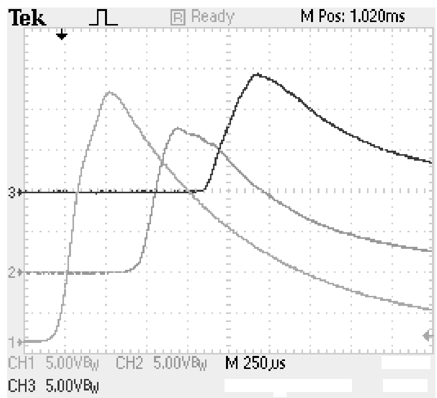


Figure 7 Representative pressure records

4 Conclusion

The investigation has confirmed a need for increase of efficiency of gas heating by pulse arc to change electric field intensity of arcing by external electrical circuit. Since the designed method lets to get an average velocity of flame propagation more than 350 m/s for 100 μs by the energy input less than 100 J. It can significantly accelerate the deflagration-to-detonation process at detonation tubes.

References

[1] Koji Yoshida et al. (1999). Performance of Newly Developed Plasma Jet Igniter. SAE Technical paper– №1999-01-3327, Book №P-348.

[2] Mayinger F et al. (1999). Flame-Jet Ignition of Fuel-Air Mixtures. Experimental Findings and Modeling. Abstracts Book ICDERS- 99 Paper No. 224

[3] Cote T et al. (1986). The ignition characteristics of igniters of sub-atmospheric pressures. Combust. Sci and Tech. 48: 151

[4] Nettleton MA (1976). Explosions due to faults in electrical equipment. Electrical review. 7:116.

[5] Zel'dovich YaB et al. (1956). Experimental investigation of spherical detonation. Journal of Tech. Phis. Rus. 26:1744

[6] Shimada H et al. (2004). Performance of Flame Jet Ignition for Pulse Detonation Engine. Science and Technology of Energetic Materials. 65:149.

[7] Korytchenko K.V et al. (2003). Investigation of a possibility to initiate detonation by plasma-wave system. Proc. of International Symposium on Combustion and Atmospheric Pollution. pp. 318-321.