Study of Heterogeneous Plasma Created by Magneto-Plasma Compressor and Erosive Capillary Discharge

A I Klimov*, N K Belov, V G Brovkin and A S Pashchina

Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia

* klimov.anatoly@gmail.com

Abstract. Magneto-plasma compressor with a pulsed capillary erosive plasma generator (MPC-EP) has been designed, manufactured and tested at the first time. This MPC-EP was used to study the physical properties of a high-energy long-lived heterogeneous plasma (ELHP) created by pulsed capillary erosive plasma generator (EP) at the wide range of pressure and temperature. The results of measurements of the parameters of the shock wave created by the MPC-EP, as well as optical spectroscopy and soft X-ray spectroscopy are presented.

1. Introduction
Magneto-plasma compressor with a pulsed capillary erosive plasma generator (MPC-EP) has been designed and created at the first time. This design is improvement of the previous one, used in plasma aerodynamic experiment [1]. Pulsed capillary erosive plasma generator creates a high-energy long-lived heterogeneous plasma (ELHP) with metal and carbon nano-clusters and hydrogen atoms [2-5]. Setup MPC-EP is used to study of the ELHP’s physical properties of at the wide range of pressure and temperature. It is obtained that this setup operates very stable at the high initial pressure up to $P_{st}$~1-10 Bar. The tested heterogeneous mixture (hydrogen atoms + carbon clusters + metal clusters) is injected into a plasma focus region. There is a real possibility to realize ELHP’s detonation in the focus region and study the interaction of hydrogen atoms and ions with carbon and metal nano-clusters at the wide range plasma parameters (initial plasma temperature $T_{st}$ and pressure $P_{st}$).

2. Experimental set up
General view of the setup MPC-EP is shown in the figure 1. The scheme of this experimental setup is shown in the figure 2. This setup has plasma jet-cathode (8) and 6 metal anodes. This setup is differed from well-known one named “plasma focus” considerably. The EP (1-4) creates ELHP with definite chemical composition and extremely high plasma parameters ($N_e$, $T_e$), [2,4,5]. ELHP’s plasma-chemical composition is determined by the erosive materials used in a capillary discharge gap (2) and in erosive electrodes (1,4). Polymethyl methacrylate (PMMA) and nickel hydride (NiHx) are used as exposed tested dielectric materials in our experiment. Electrode material is a copper. ELHP obtained by the EP is ignited and compressed by MPC at the definite time delay $t_d$~0.1-3 ms after its creation. ELHP’s detonation is realized in this experiment. Parameters of shock waves created by ELHP’s explosion are studied in this work.
3. Shock wave created by the MPC-EP
Pressure distribution $P_2(X)$ behind shock wave (SW) front created by MPC-EP and mean SW velocity $V_{SW}(X)$ are measured in this work. Schematic representation of experimental setup used in this work.
The experiment is shown in the figure 3. One can see MPC-EP (1) with capacity storage (4) and pressure sensors (2) in this picture.

The structure and evolution of a heterogeneous plasmoid, created by MPC-EP, was studied by a high-speed video camera also, figures 4-6.

Anisotropic pressure distribution behind SW was revealed in our experiment, figure 5. SW- front was not spherical. This result was obtained by shadow method also.

It is obtained that Mach number of the SW is about $M_{SW} \approx 1.3$ at the distance $X = 10$ cm from MPC-EP’s location. Testing insertion in the capillary gap is $C_5H_8O_2$ in this experiment. So, a weak SW is created at the distance $X > 10$ cm. These results were obtained both pressure method and time delay method (velocity measurement method) with accuracy 3%. The mean velocity of plasma-air contact surface $V_p \approx 500-600 \text{ m/s}$ was measured by a high-speed video camera, figure 6. Maximal heterogeneous plasma volume was $W_p \approx 50 \text{ cm}^3$ at the typical time delay from ignition $t_d \approx 20 \mu\text{s}$.

One can obtain the value $P_2$ behind SW front at the Mach number $M \sim 1.3$ and the distance $X = 10$ cm by using well-known relation on the SW front:

$$P_2 = P_1 \left( \frac{2M^2}{\gamma+1} + \frac{\gamma-1}{\gamma+1} \right),$$

where $\gamma = 1.4$ and $P_1 = 2.14 P_f$.

Thus, pressure jump on SW front is about of $\Delta P_2 = P_2 - P_1 = 1.14 P_1 = 1.14 \text{ Bar}$

(1)

Extrapolation of the curve 3 in figure 5 to the point $X \approx 4-5$ cm (boundary location of the plasma contact surface, see figure 6) helps us to estimate pressure jump on the SW front near this region

$$\Delta P_2 \approx (10/5)^2 \cdot 1.14 \approx 4.56 \text{ Bar}$$

(2)

The detonation energy $E_d$ may be estimated by (2) and using the measured value $W_p \sim 50 \text{ cm}^3$ (see above):

$$E_d = \Delta P_2 \cdot W_p \sim 23 \text{ J}$$

(3)

The very closed values $\Delta P_2^*$ and $E_d^*$ may be obtained by the measured value $V_p \sim 600 \text{ m/s}$ (see above) using well-known relation on the SW front:

$$V_p = M_{SW} C_s (1 - \rho_1/\rho_2),$$

where $C_s$ – sound velocity, $\rho_1$, $\rho_2$ – gas density before and behind SW front.

From the relation (4) one can obtain the value Mach number $M_{SW} \sim 2.18$ and the value $(P_2/P_1)^* \approx 5.7$ in air near plasma contact surface. Thus, the value $\Delta P_2^* = P_2^* - P_1^*$ is about of $\Delta P_2^* \sim 4.7 \text{ Bar}$. One can see that this value $\Delta P_2^* \sim 4.7 \text{ Bar}$ is close to value $\Delta P_2 = 4.56 \text{ Bar}$ (2).

It was revealed that SW- strength depends on the composition of tested chemical materials used in a discharge capillary gap considerably (such as $C_5H_8O_2$, NiHx). Minimal pressure $P_2^*$ was measured at the case of PMMA using ($C_5H_8O_2$- monomer). Maximal pressure $P_2^{**}$ was measured at the NiHx injection into the plasma focus region. The ratio $P_2^{**}/P_2^*$ was about of 1.5. Suppose that this value may be connected with the additional energy release $\delta E_{ch}$ connected with the specific plasma-chemical reactions inside ELHP. So, this value may be estimated by the following formula

$$\delta E_{ch} = (0.5)^* E_d \sim 0.5 \times 23 \text{ J} = 12 \text{ J}$$

The value of the NiHx mass erosion flow $\delta M_{er}$ was measured in this experiment. This value is about of $\delta M_{er} = 1.2 \text{ mG/discharge}$. The specific energy $q_x$ of these reactions is about of

$$q_x = \delta E_{ch} / \delta M_{er} = 12 \text{ J} / 1.2 \text{ mG} \sim 10 \text{ kJ/G}$$

Note that this value exceeds the typical value of the TNT by factor

$$K = q_x / q_{TNT} = 10 \text{[J/G]} / 4.2 \text{[J/G]} \sim 2.4$$
Figure 3. Scheme of the SW experiment, 1 – MPC-EP, 2 – pressure sensors, 3 – high-voltage probe, 4 – capacity storage.

Figure 4. The frame of high-speed video with MPC-EP operation regime.

Figure 5. Pressure dependence P2 (X) behind SW front (relative units) on distance X between pressure sensor and MPC-EP. Red - along MPC-EP axis, blue - perpendicular direction.
Figure 6. High-speed video frames of the plasma-air contact surface propagation created by MPC-EP. Frequency -100000 frames/sec, exposure time ~200 ns. Diameter of MPC anode’s electrode – 5 mm.

4. Optical spectra and soft X-ray spectra from the ELHP
The optical spectra from ELHP, created by MPC-EP were recorded by the optical spectrometer AvaSpec 2048, figure 7. These spectra were processed and analyzed. It is obtained that there are the atomic optical H, K, Ni, Na, Li lines and continuum bands in these spectra. These continuum bands
are connected with metal nano-clusters creation inside ELHP [6]. Black-body temperature of these metal nano-clusters $T_b \approx 3000 \div 4000$ K are estimated by these optical spectra.

![Figure 7. ELHP’s optical spectra. Small concentration NiH$_x$ injection in plasma focus region – green, without this injection – red, blue – NIST simulation.](image)

It is revealed that there are the intensive optical Li lines in the ELHP’s spectra at NiH$_x$ dusty particles injection into a plasma focus region (figure 7, green plot). Note that the lithium atoms are absent in the initial chemical elements filled a discharge capillary gap. This result is not clear up today and will be studied in future experiments.

It was recorded an intensive soft X-ray radiation ($E_x \sim 1$ KeV) by spectrometer X-123, figure 8. It was measured a cold neutron flux from HP in this experiment also.

![Figure 8. The typical soft X-ray radiation spectrum](image)
5. Conclusions
1. Magneto-plasma compressor with a pulsed capillary erosive plasma generator (MPC-EP) has been designed, manufactured and tested at the first time. This MPC-EP was used to study the physical properties of a high-energy long-lived heterogeneous plasma (ELHP) created by pulsed capillary erosive plasma generator (EP) at the wide range of pressure and temperature.
2. Pressure distribution $P_2(X)$ behind shock wave (SW) front created by MPC-EP and mean SW velocity $V_{SW}(X)$ were measured in this work. It is revealed that there is anisotropic pressure distribution behind SW. So, SW- front is not spherical one.
3. It is revealed that SW- strength depends on the composition of tested erosive chemical materials (such as C$_5$H$_8$O$_2$, NiH$_x$) filled the discharge capillary gap considerably at the same electric discharge parameters. Supposing that additional energy release behind SW front is connected with specific plasma-chemical reactions inside the ELHP it is easily to obtain the value of specific reaction energy release $q_x \sim 12\text{kJ/g}$. This value exceeds the typical TNT detonation one by factor $K = q_x/q_{\text{TNT}} \sim 2.4$.
4. The optical spectra of the ELHP, created by MPC-EP, were recorded in this work. Estimated black-body temperature $T_x$ of the erosive clusters inside ELHP is about of $T_x \sim 3000 \div 4000$ K. It is revealed that there are intensive optical Li lines in a heterogeneous plasma at the NiH$_x$ dusty particles injection into plasma focus region. Note that the lithium atoms are absent in the initial chemical element composition used in a discharge capillary gap.
5. There is an intensive soft X- ray radiation ($E_x \sim 1\text{keV}$) from the ELHP measured by a spectrometer X- 123. It was measured a cold neutron flux from the ELHP in this experiment also. The results indicated in the items 4 and 5 are not clear up today and will be studied in future experiments.

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