12. SHOCK WAVE PROPAGATION THROUGH NON- EQUILIBRIUM CLUSTER PLASMA

Klimov A., Bityurin V., Charitonov A., Fokeev V., Sakharov A., Vystavkin N., Kuznetsov A.
Institute for High Temperature RAS
Moscow, Izhorskaya 13/19 e-mail: aklim@orc.ru

Introduction

The propagation of acoustic and shock waves (SW) through weakly ionized non-equilibrium plasma (WINP) was studied in our previous works [1-4]. The unusual physical properties of the cluster plasmoid created by erosive pulse discharge were considered in [5]. Present work is devoted to study of the SW propagation and its structure in cluster WINP. Cluster plasma was created by erosive pulse discharge in test section of the shock tube ST-5. The cluster plasma parameters were measured in this work. The SW Mach number was $M < 5$. It was revealed that the cluster plasma with small concentration of cluster particles ($< 10^8$ cm$^3$) could change SW structure in the WINP dramatically (more effectively than plasma without cluster particles). The electric potential generated on the SW front in cluster plasma was measured by the electric probes. The comparison between experimental and theoretical results is discussed in this work also.

The experimental results on the SW structure and its propagation in WINP (without clusters) were considered in our previous works [1-3,6]. It was revealed that

1. The experimental results are very closed to the thermal ones (explained by average gas heating in plasma) in the case of the continuous electric discharge with small current density ($j < 100$ mA/cm$^2$) and weak SW ($M < 2$), [6].
2. The experimental results are non-thermal ones in the case of the electric pulse discharge with large current density ($j > 100$ mA/cm$^2$) and strong SW ($M > 2$), [6].
3. The average gas heating of homogeneous plasma cannot explain these results. The heterogeneous (structural) plasma approach is the correct one and can explain these results only.

According our opinion the heterogeneous plasma with thin plasma filaments and its physical properties (see item #2) play important role in the SW structure modification and its acceleration in the WINP. Meta-stable excited molecule condensation stimulated by the SW (plasma instability generation) helps us to explain non-thermal experimental results. So, study of the plasma structure generation behind SW front and its physical properties is very important. The optimal conditions of plasma structure generation (condensation) are the followings [3]:
- Low gas temperature (cold plasma, airflow, and others), $T_g < 600$K,
- High concentration of meta-stable excited molecules, $N^* > 10^{12}-10^{14}$ cm$^3$,
- High pressure behind a SW front $P > 100$Torr,
- Cluster concentration $n_d > 10^7$ cm$^3$,
- Electric double layer generation on SW front.

The preliminary experimental results on SW propagation and plasma-ballistic experiment in dusty (aerosol) plasma were obtained in our works ten years ago. Some of them are considered in [6]. It was revealed that small dusty particle concentration (about $10^7$ cm$^3$) in plasma increases
- SW velocity in a WINP,
- SW front splitting,
- Head SW standoff distance near spherical model (up to 2-3 times).

High electric potential generation on the SW front (up to $100-1000$ V) in cluster plasma was obtained in the theoretical work [7].

Main goals of the present work are the followings

1. Generation of the homogeneous and non-homogeneous cluster plasmoid in the shock tube test section.
2. Measurement of the electric potential in cluster plasmoid.
3. Study of the SW structure and its acceleration in cluster plasma (without external electric field).

The scheme of the experimental set up ST-5 used in the present experiments is shown in Fig.1. Charged clusters were generated by the erosive plasma generator (PG-jet, 1), [3]. This PG is installed in the dielectric test section (5) of the shock tube. The electric probes (3) are installed in this test section also. The electric potentials on the SW front in cluster plasma were measured by these probes. External transverse electric field used in this experiment also. The diagnostic instrumentation of the set up ST-5 consists of
- Shadow photography with small expose time (30-40 ns) for SW structure study,
- Streak film camera for the SW velocity measurement in cluster plasma,
- Electron microscope for the cluster geometry measurement,
- Pressure transducers,
- Optic spectroscope,
- Optic micro-pyrometer.

The acoustic experiment scheme in the setup ST-5 is shown in Fig.2. Acoustic resonator (quartz tube) was connected with erosive plasma generator. The microphone was located in the definite distance from open tube end.
Main experimental results

1. Two different cluster plasma formations (plasmoids) were created in the test section of the ST-5, Fig.3. The plasmoid velocity $V_j$ was about 200m/s (air, ~40Torr). The average cluster diameter was about 0.1≈1mcm. The mean cluster concentration was about $N_d=10^7$≈$10^8$cm$^3$. These cluster particles consist of pyro-graphite Fig.4.
2. The turbulent gas dynamic shell (layer) was created around erosive plasma jet, Fig.5 (top).
3. The weak SW and ring plasma vortex were generated before cluster plasmoid.
4. The negative electric potential about 100-300V was measured in the head part of cluster plasmoid.
5. The gas temperature $T_g$ in the cluster plasmoid was measured by three different independent diagnostic methods: acoustic method, micro-pyrometer method, optical spectroscopy. The measured gas temperature was about $T_g=1000$-1100K, (air, ~ 40Torr). The characteristic acoustic signal recorded by the microphone is shown in the Fig.7. Gas temperature was reconstructed from this signal processing. It

Fig.3. Cluster plasma jet in the test section of the ST-5 (air, ~40 Torr).

Fig.4. Electron microscope photo of pyro-graphite clusters.
was obtained that the gas temperature depended on the initial gas pressure, Fig.8.

6. The interaction of the incident SW with the cluster plasmoid is shown in Fig.9 (down). One can see that there is the SW acceleration in cluster plasma. The SW velocity \( V_p \) in cluster plasma was measured about 1270±63 m/s at the incident SW velocity about 900±30 m/s, (air, ~40 Torr).

7. The SW front is curved in the cluster plasmoid, Fig.10. Note that there is invisible SW front near cluster plasma jet axis.

8. There is the SW instability in cluster plasma.

9. The measured electric potential amplitude on the incident SW front (or reflected SW front) is about 100±300V, (air, ~40Torr). These measurements were carried out by the resistive and capacity dividers, Fig.6.

Fig.5. Shadow photo of the cluster plasma jet in the test section ST-5 (air, ~40 Torr)

Fig.6. Electric probe signals obtained in the test chamber of the ST-5 (air, ~40Torr, \( V_0=900\text{m/s} \))

Fig.7. Pressure signal recorded by the microphone in cluster plasma, air, \( P_0 \sim 47 \text{ Torr} \)

Fig.8. Dependence of the gas temperature \( T_g \), in cluster plasma on initial gas pressure (acoustic experiment)
Discussion

1. One can suppose that there is the energy release in cluster plasma jet. The turbulent gas dynamic disturbances generated by plasma jet prove this conclusion, Fig.5 (top). Pressure transducer recorded the pressure fluctuations near plasma jet also.

2. The gas heating in cluster plasmoid cannot explain SW acceleration in cluster plasma. Really the gas temperature $T_g$ needed for explanation of the experimental results is about $T_{g,th} \sim 1600$K (remember that the measured SW velocity in cluster plasma is $V_p=1270\pm63$ m/s and measured plasma jet velocity is $V_j\sim 200$ m/s). Note that the measured gas temperature in cluster plasmoid is less then 1100K (see item #5). This theoretical gas temperature estimation was obtained on the base of the 1-D simulation [6]. According to the 2-D simulation this gas temperature has to be higher than $T_{g,th} \sim 2000$K. So, the theoretical gas temperature value needed for the SW acceleration in cluster plasma is much higher than the experimental one, $T_{g,exp}=1100$K. We suppose that the energy release in cluster plasma behind SW front takes place in our experiment. This question will be studied in future experiments.

3. Methodic remarks. One can see that there is invisible SW front near plasma jet axis, Fig.10. So, it is possible to do some mistakes of the correct SW velocity measurement in cluster plasmoid by the shadow method [9,10]. It is very important conclusion. So, it is need to use the pressure measurement and shadow...
measurement on the SW front in plasma simultaneously.

4. Every cluster has about $10^3$ elementary electric charges. Average cluster potential could be 100-1000V. These cluster characteristics were obtained in the work [8] at the conditions closed to our experimental ones. So, the cluster plasma is the non-ideal one in our experiment. The non-ideal plasma parameter of this plasma is about 1 and higher. So, very strong collective properties are in this cluster plasmoid. The maximal electric current recorded by the probe was about $3 \times 10^{-4}$Amp. This value is very closed to the theoretical one $I_{pb} \approx V_d N_d q S$, where $V_d$ – velocity of plasma jet, $N_d$ – cluster concentration, $q$ – cluster electric charge, $S$ – probe’s square.

5. One can suppose that the SW instability in cluster plasma is created by the double electric layer generation on the SW front.

References