Abstract. The shock wave structure in weakly ionized ionic plasma with the presence of negative charged nano-particles is studied on the base of a complex approach including the solution of the Boltzmann’s equation and the Poisson’s equation applied to the region of fast variation of the microscopic parameters (at the distance of several free path lengths) and the solution of the set of equation for the multi-temperature, multi-velocity gas dynamics of the chemically reacting weakly ionized plasma. It is found that in such a plasma where the major portion of electrons is bound (i.e. the conditions $n_e << n_i$, $\delta n_e \leq \delta n_i$ are valid) a ‘super-bulldozer’ effect can be observed. This effect is that the shock propagating through such a media captures the free electrons. In the region of several tens of free path length the fast compression of the electron up to $- 4n_i(e^{-\infty})$ gas has occurred resulting in electron number density elevation in four order of magnitude. Consequently its temperature increases in approximately 1000 times. Behind this region a zone of high concentration of electrons is formed. The electron temperature approach the equilibrium level at the distance of $m_e \lambda_{en}$ (where $m_e$ – the electron mass, $m_n$ – the neutral carrying gas mass, $\lambda_{en}$ – the free path length of electrons). In this rather extended region the intensive physical-chemical processes (such an electron excitation of molecules) resulting in molecule dissociation and primary radicals formation take place. In particular, these processes can affect significantly on induction time of chain reaction.

Introduction

Even in pioneering works by N. Tesla it was found that the plasma containing the electrode erosion products or specially evaporated wax substrates reveals unique properties. In particular, the long life duration (0.1-1sec) of plasma formations was outlined. Later such results were confirmed in a number of experimental studies (see, for example, [1,2]) where besides of long life duration many others interesting features taking place in these physical environment are found.

In theoretical studies [3-5] the description of the shock wave structure in ionic dust or cluster plasma has been given first on the base of complex approach involving the solutions of Boltzmann’s and Poisson’s equations along with the solution of multi-temperature multi-velocity gas dynamics. Such a plasma is considered occurring in erosion of electrodes or substrates. A number of new ‘anomalous’ effects in such plasmas were predicted in that study. It is notable that the important condition of the ionic plasma: $n_e << n_i$, $\delta n_e \leq \delta n_i$ (where $n_e$ and $n_i$ – electron and ion number densities, $\delta n_i$ – the number density of positive and negative charged particles (clusters)). The most important results reported in [3-5] is the prediction the effect of cumulative energy – the mechanism of high kinetic energy (100keV – 10MeV) transfer from heavy particles (clusters) to ions and/or electrons through the self-sustain electric field. The latter is created by charged separation at the flow discontinuity. This effect can lead to the breakdown and/or (depending on the plasma and shock wave parameters) to the initiation of intensive physical-chemical processes that, in turn, can result in the chain avalanche reactions [6]. It was shown [3-6] that the shock wave front could play a role of an effective plasma-chemical reactor. The important feature of multi-scale nature of the shock wave front under such conditions has been found for several particular cases in paper [4]. Zones of fast parameter variation $\delta \leq 10 \lambda_e$ and one-two zones of slow variations $\delta \leq 100 \lambda_e$, $\delta \leq 10^3 \div 10^4 \lambda_e$ are specified where $\delta$ – zone size, $\lambda_e$ – electron free path length. The partial temperature and velocities of the gas components could significantly differ in different zones.

On the base of the results obtained in [4] authors have developed an approach of the description of the shock wave structure in a weakly ionized cluster plasma consisting of the solution of the Boltzmann’s equation in fast variation zone and utilization of this solution as initial and boundary conditions for the multi-velocity multi-temperature gas dynamics equations and chemical kinetics equations for zones of slow variation. It provides to describe the shock wave structure in complex
chemically reacting mixtures including more than 50 reactions and many components. It was reported in paper [6] that the presence of charged particles or clusters in ionic reacting plasma could result in significant reduction of the induction time of chain reactions important for practical applications. It is known [7] that clusters can get charge of different polarity. For the case of positive charged particles it was found in [3-4] that electrons are accelerated in shock wave front. For the negative charged particles the electrons are decelerated and accumulated upstream the shock wave front. Thus, depending on particle charge the shock wave reveals the different structure. The shock wave in weakly ionized ionic plasma with negative charged particles is characterized by three zones: a zone of fast variation and two zones of slow variation. The thickness of these zones depends on flow and mixture parameters.

**Approach.**

In this paper two slow variations zones: $\delta_2$ where the electron number density increasing to compensate excessive electrical space charge, and $\delta_3$ where the cluster concentration reaches the equilibrium level: are described with the multi-temperature, multi-velocity gas dynamics equations (compare [5,6])

$$\frac{\partial n_s}{\partial t} + \frac{\partial n_s u_s}{\partial \xi} = \frac{1}{2} \sum_{a,b,c} (k_{ab} n_a n_b - k_{db} n_a n_s)$$  \hspace{1cm} (1)

$$\rho_s \frac{d u_s^V}{d t} + \frac{\partial}{\partial \xi} (\rho_s u_s^V \beta_s - e_s n_s E^V) = \Delta Q_s^V$$  \hspace{1cm} (2)

$$\frac{3}{2} n_s k_s \frac{d k_s}{d t} + p_s^V \beta_s \frac{d u_s^V}{\partial \xi} + \delta_s^Q = \Delta Q_s^Q$$  \hspace{1cm} (3)

$$\text{div} \mathbf{E} = \frac{1}{\varepsilon_0} \sum_s n_s e_s$$  \hspace{1cm} (4)

where $n_s$, $u_s$, $T_s$ – partial concentration, velocity, and; $p_s^V$, $\beta_s$ – pressure tensor; $p_s^V = \delta_{ss} p_s - \sigma_s^s$; $\beta_s^\gamma$ – partial pressure; $\sigma_s^\gamma$ – viscous tension tensor; $q_s^k$ – heat flux ; $m_{si} = \frac{m_i m_i}{m_i + m_j}$, $m_i$ – particle mass; $\rho_s$ – partial density; $e_s$ – particle charge; $k_{sd}$ – rate constant of non-elastic process:

$$\Delta Q_s^\gamma = \sum_{s \neq \tau} m_s n_s \nu_s \Omega_s^{(1,1)} (u_s - u_s) E_s$$  \hspace{1cm} (5)

$$\Delta Q_s^Q = \sum_{s \neq \tau} m_s n_s \nu_s \Omega_s^{(1,1)} \left[ \frac{3k(T_s - T_\tau)}{m_s + m_\tau} + u_s^2 E_s \right] + \frac{1}{2} \sum_{a,b,c} \left( u_{ba} E_{ba} n_a n_b k_{ba} - u_{ds} E_{sd} n_s n_d k_{ds} \right)$$

(6)

where $\Omega_s^{(1,1)}$ – Chapman-Enskog’s omega integral, $E_{sd}$ – non-elastic process activation energy. The others references related to (1)-(6) can be found in [5,6]. In fast parameter variation region $\delta_s \leq 10 \lambda_s$, the Boltzmann's equation along with the Poisson’s equation are utilized:

$$\frac{v_s}{m_s} \frac{d f_s}{d \xi} = \frac{e_s E}{m_s} \frac{d f_s}{d \sigma_s}$$  \hspace{1cm} (7)

$$\frac{d E}{d \xi} = \sum_i n_i e_i - \varepsilon_0$$  \hspace{1cm} (8)

where $E$ – electric field strength, $g$ – relative velocity, $\Delta \Omega$ – space angle, $\sigma(\gamma, \chi)$ – collision cross-section, $v_s$ – molecular particle velocity, $\varepsilon_0$ – electric permeability. Due to the small thickness of this zone $\delta_s$, a small but still finite portion of particles reacts there. For this reason the influence of the chemical transformation on the flow can be neglected as the first. This fact is reflected in equation (7) where the terms responsible for chemical transformation are omitted. The influence of the flow on the chemical transformation is important and it is taken into account by the distribution function derived from (7) in the expression $k_{sd}$:

$$k_{sd} = \int f_s(x, v_s) f_s(x, v_s) \cdot \frac{p_{ab}}{\varepsilon_0} \sigma(\gamma) \Delta \Omega d^3 \chi$$

The latter are used later in source terms of continuity. This approach is described in all details in paper [8].

The description of weakly ionized plasma in the upstream part of the shock wave front is based on successive approximations process (see [8] for details). In this case the reduced equations derived from (1-8) are as:

$$\frac{d p}{d \xi} = - e E n_e$$  \hspace{1cm} (9)
\[ T_e = \left( \frac{n_e}{n_{le}} \right)^{2/3} T_l \]  
\[ \frac{dE}{dx} = \frac{1}{\xi_0} \left( n_e + \epsilon \psi n_{li} f(x) + \epsilon \psi n_p \right) \]  
\[ f(x) = \frac{1}{1+e^{Bx}} + \frac{u_1}{u_2} \frac{e^{Bx}}{1+e^{Bx}} \]  
where \( P_e = n_e kT_e \) – electron partial pressure; \( n_{le}, n_{li}, n_p \) – electron, ion, cluster number density in oncoming flow; \( z_i, z_p \) – charge numbers of ion and clusters; \( f(x) \) – the function characterizes the ion and neutral particle variation derived from analysis of (7), (8) [5,6] and [9]; \( u_1 \) – flow velocity at \( \infty \), \( u_2, T_2 \) – velocity and temperature behind the fast variation zone (note that \( u_2, T_2 \) are not equal to \( u_{ion}, T_{ion} \), where the mixture is in equilibrium). The expressions for \( u_2, T_2 \) and the method of its definition are presented in [5,6]. The value \( B \), used in (12) \( B \sim 4 \delta, \delta = 4 \lambda \delta \sim 0.8-1.2 \) (see [9]). The solution of (9)-(12) can be found numerically. In order to start numerical integration an analytical solution in the vicinity of singular point at \( \infty \) should be obtained. The analytical solution is found by standard linearization of (9)-(12) and neglecting of non-linear members in the \( e \)-vicinity of singularity. This yields:
\[ \psi = c_1 e^{\sqrt{A} t} + \frac{A^2}{A - s^2} e^{\sqrt{s} t} \]  
where \[ A = \frac{3 \kappa_e n_{li} \epsilon_{li}^2}{5 \xi_0 k T_{le}}, \quad z = z_i \frac{n_i}{n_{li}} \left( \frac{u_1}{u_2} - 1 \right), \] \[ \kappa_e = \frac{n_{te}}{n_{le}}, \quad \kappa_i = \frac{n_{ti}}{n_{le}}, \quad n_{le}, n_{li} \] – neutral particle concentration in oncoming flow, \( e \) – electron charge, \( \epsilon = \lambda \lambda_i \), \( \lambda_i \) – free path length, \( n_i/n_{le} = 1 + \psi \). An unknown constant \( c_1 \) is presented in (13). This reflects the fact that the values \( T_e \) and \( E \) behind the fast variation zone are unknown instead of \( T_e(\infty), E(\infty) \) in downstream equilibrium zone are specified. For this the equations (9)-(12) are to be integrated along with the full set of (1)-(4) (in zone of slow variation \( \delta_i \), utilizing the results of solution of (9)-(12) as the boundary conditions for (1)-(4). The solution of (9)-(12) with (1)-(4) is found by probe and faults method.

**Discussion**

A ‘super-bulldozer’ effect is predicted on the base of the solution of the problem on the shock wave structure in the weakly ionized ionic cluster plasma for the case of negative charged clusters. The essence of the effect is that for the condition \( n_{le} \ll \lambda_{le} \sim \lambda_{le} \ll n_{le} \), the electrons are raked up by the shock wave. The electron number density can increase by several order of magnitude up to \( n_{le} \sim n_{le} \), in depending on the initial \( n_{le} \). In limiting cases the compression of electrons in the upstream part of the shock wave front \( \delta_i \) can occur adiabatically and isothermally as well. For practice the adiabatic compression is more interesting because of the strong electron temperature elevation resulting in intensive physical-chemical processes. It is notable that the electron velocity is practically equal to the shock wave velocity. Thus, the shock wave carries not only momentum and energy but mass as well. The calculation of the shock wave propagation in a weakly ionized ionic plasma with negative charged clusters has been carried out for the parameters specified in the Table 1.

<table>
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<th>( N )</th>
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<td>( 10^9 )</td>
<td>( 10^8 )</td>
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<td>1</td>
<td>( 0.42 \times 10^{-3} )</td>
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<td>( z )</td>
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<td>-10</td>
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Here numbers \( N = 1 \), \( 2 \), \( 3 \) - for electrons, \( N = 4 \) – for clusters, \( \kappa_i = \frac{n_i}{n_{le}} \) – charged particle number density reduced to carrying gas number density, \( R = \frac{m_i}{m_n} \); \( d = \frac{d_{le}}{d_i} \) – the ratio of the effective diameter of charged particle and carrying gas molecule, \( z_i \) – charge numbers. The shock wave Mach number is \( M = 3.1 \).

In Fig.1 and Fig.2 the electron number density \( \frac{n_e}{n_{le}} \) variations over the shock wave front are presented in different scale versus \( x/\lambda_i \), where \( x \) – distance, \( \lambda_i \) – the free path length in oncoming flow. It is seen from the figures that the electron number density increases in two order of magnitude. The thickness of the upstream part of the shock wave front is about \( \delta_i / 40 \lambda_i \). For comparison in Fig.3 the variation of the reduced number density \( \frac{n_{le}}{n_{le} - 1} \) vs \( x / \lambda_i \) for carrying gas (solid curve) and clusters (dashed curve) are presented. A two-side structure is clearly recognized from the Fig.3: \( \delta_i \) – the fast variation zone, \( \delta_i \) – the slow variation zone.
The reduced $\frac{T_e}{T_i} - 1$ temperature variation in the shock wave front is exemplified in Fig.4. It is clearly seen that the electron compression is practically adiabatic (for the case specified in Table 1). The electron temperature excess the equilibrium level behind the shock in 35 times. In Fig.5 the variation of the reduced temperature of ions and neutral carrying gas (curve 1) and clusters (curve 2) are presented. The two-scale feature of the distribution is obvious.

The electric field (in Td) variation is presented in Fig.6. The characteristic details is that the sign change in the shock wave front. This result differs from the earlier obtained [6] for the case of
positive charged clusters when the electric field sign was unchanged.

Figure 6 The reduced electric field strength distribution

At the same time the space charge distribution presented in Fig.7 looks similar to the previously considered cases.

Figure 7 The space charge distribution

The corresponding potential distribution is shown in Fig.8 where the potential maximum reflects the fact of the electric field sign change.

Figure 8 The electrical potential distribution

The variation of the reduced oxygen atom number density $\gamma = \frac{n_O}{n_{O_2}}$ produced by the oxygen molecule dissociation in the process of electron excitation and further flying away:

$$O_2 + e \leftrightarrow O_2^* + e \leftrightarrow O + O + e$$  (14)

is presented. The analysis of the hydrogen-oxygen combustion, for example, has shown that the $O$ radical production under such condition could be enough to decrease the induction time in order(s) of magnitude.
Concluding Remarks.

1. The structure of the shock wave in a weakly ionized ionic plasma with clusters differs significantly for the cases of negative and positive charged clusters:
   a) in the case of negative charged clusters the electrons are decelerated and its concentration increases in the shock wave front;
   b) in the case of positive charged clusters the electrons are accelerated and its concentration drops.

2. The ‘super-bulldozer’ phenomenon is predicted. The phenomenon is that the electrons are reflected by the negative potential barrier created by the shock wave propagation through such plasma, and accumulated in the upstream zone of the shock wave front.

3. The electron compression can occur as adiabatic and isothermal as well depending on the flow conditions.

4. The electrons move with velocity practically equal to the shock wave velocity so the shock wave carries not only the momentum and energy but and the mass as well. The shock wave character is similar in some way to the case of a single wave – solution.

Acknowledgement

The work is partially supported by RFBR Grant №00-02-16644a.

References