Nonequilibrium Processes in Nitrogen Plasma Behind Strong Shock Waves

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1 Introduction

The kinetics of processes behind a shock wave propagating in a gas are determined by a combination of various phenomena: excitation of internal (rotational, vibrational, and electronic) degrees of freedom of molecules, dissociation and chemical reactions, ionization and ion-molecular reactions, radiation, variations of the temperature and pressure. The intensity and significance of these processes depend on the initial state of medium and the shock wave intensity, and the way they succeed each other is determined by the hierarchy of the characteristic times and depends on the gas temperature T and pressure P. For past decades a great progress has been achieved in the description of vibration-chemistry coupling in thermally nonequilibrium conditions behind strong shock waves [1-3]. The reaction mechanisms of ion and electron origin in high temperature gas in post shock region were also built [4]. The reviews on this problem were regularly published in proceedings of international workshops and conferences (see, for example, [5-7]).

Significantly less findings were addressed to the problem of the formation of electronically excited particles (both atoms and molecules) in the post shock region and their effect on the processes of charged species formation. It is worth noting that namely electronically excited atoms and molecules are responsible for the intensity and spectrum of the radiation produced by plasma behind shock wave. Nevertheless, the most of the published kinetic models developed to describe the processes of the neutral and charged species origin in a high temperature gas behind shock waves do not involve the reactions with electronically excited particles.

This work is focused on the modeling studies of processes leading to formation of electronically excited atoms and molecules in the high temperature gas behind the shock wave and on the influence of these processes on plasma composition. The analysis was undertaken for nitrogen or nitrogen-argon plasmas, which were widely investigated previously by different researchers.

2 Kinetic model

In the most practically interesting cases, the processes of vibrational relaxation, dissociation, formation of electronically excited molecules as well as ion and electron origin are strongly coupled. This dictates a necessity to build a kinetic model that takes into account such interconnection. In our consideration it is assumed that the rotational and translational degrees of freedom are in a

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thermodynamic equilibrium and inside nitrogen mode there exists a local Boltzmann distribution with its own vibrational temperature T_{N_2}.

Besides plasmachemical reactions with neutral and charged particles the model includes the processes of vibrational-translational (V-T) relaxation, electronic-electronic (E-E) exchange, electronic-translational (E-T) relaxation, excitation of vibrational and electronic states of molecules, dissociation and ionization due to electron impact as well as reactions of associative ionization, electron attachment and formation of electrons via ion-molecule interaction. The model treats following neutral unexcited: N, N_2, Ar and electronically excited species: $N(^2D)$, $N(^2P)$, $N_2(A^3\Sigma_u^+)$, $N_2(B^3\Pi_g)$, $N_2(a^1\Sigma_u^-)$, $N_2(C^3\Pi_u)$, $N_2^+(A^2\Pi_u)$, $N_2^+(B^2\Sigma_u^+)$ as well as N^+, N_2^+, N_4^+, Ar^+ ions, and electrons.

3 Results and discussion

Consider the nonequilibrium processes in nitrogen plasma produced by strong shock wave. A number of researches were focused on the measurements of the radiation intensity in the $N_2(1+)$ band ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$ transition) and in the $N_2^+(1-)$ band ($B^2\Sigma_u^+ \rightarrow X^2\Pi_g$ transition) behind the shock front depending on shock wave velocity. Some works besides the radiation intensity reported the data on the variation of time instance t_m at which the radiation intensity of these bands achieved its maximal value [8]. These data was utilized to validate the developed kinetic model. Figure 1 shows the variation of the parameter $\tau_m = t_m \cdot P$ versus velocity of incident shock wave V for $N_2(1+)$ and $N_2^+(1-)$ bands in N_2/Ar = 1/9 measured in [8] and predicted using the kinetic model of the present work. As is seen, the consistence between measurements and predictions is quite good. This means that the model describes properly the temporal evolution of flow parameters and concentrations of excited N_2 molecules and N_2^+ ions behind the shock front.

The typical spatial profiles of gas and electron temperatures, vibrational temperature of N_2, and species concentrations downstream the shock front are shown in Figures 2 and 3. First of all, one can see that in N_2/Ar mixture for conditions considered (V = 3.4 km/s and gas temperature just behind the shock front $T_1 \approx 10000$ K) the thermodynamic equilibrium between vibrational and transitional degrees of freedom is established faster than the plasmachemical reactions become essential. Therefore, the formation of ions and electrons as well as electronically excited species can be considered at such conditions using thermally equilibrium kinetic model. The calculation proved this supposition and showed that the behaviors of τ_m parameter versus shock wave velocity for the emission both in $N_2(1+)$ and in $N_2^+(1-)$ bands predicted by thermally equilibrium and thermally nonequilibrium models differ only slightly. The second interesting fact that follows from the plots shown in Fig. 3 is that the dominant charged species in N_2/Ar plasma are Ar^+ ions and electrons. The other important ion in the nitrogen-argon plasma is N^+.

It is interesting to clarify how the neglect of electronically excited atoms and molecules in the model can change the predicted values of electron and ion concentrations. Figure 4 demonstrates the difference in the maximum value of electron mole fraction predicted by the models with the allowance of electronically excited species and without it versus shock wave velocity in pure N_2. As can be seen, at V > 7 km/s the model ignoring the electronically excited species underestimates twice the maximal value of electron and N^+ ion concentrations. At the shock wave velocity V < 5 km/s the influence of electronically excited species on the $\gamma_{e,\,max}$ value becomes negligible.

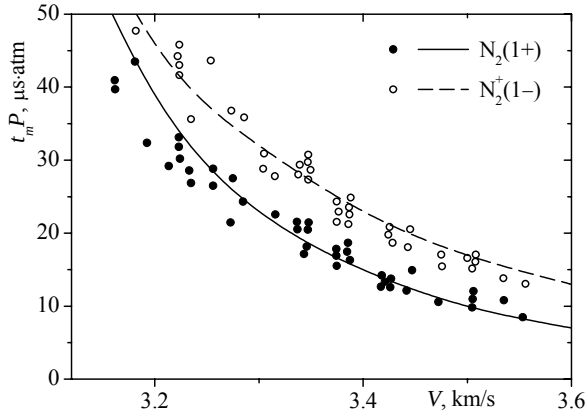

Fig. 1. Variation of the predicted (lines) and measured (symbols) τ_m parameter for $N_2(1+)$ and $N_2^+(1-)$ band radiation in $N_2/Ar = 1/9$ mixture vs. shock wave velocity at $T_0 = 300$ K, $P_0 = 6$ torr.

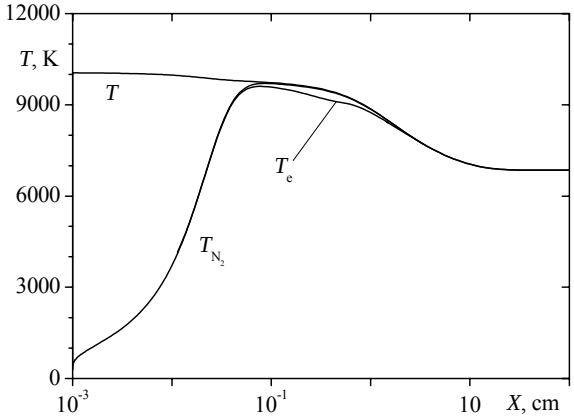

Fig. 2. Variation of gas temperature T, electron temperature T_e, and vibrational temperature of N_2 T_{N_2} downstream the shock front in $N_2/Ar = 1/9$ mixture at $P_0 = 6$ torr, $T_0 = 300$ K and shock wave velocity $V = 3.4$ km/s.

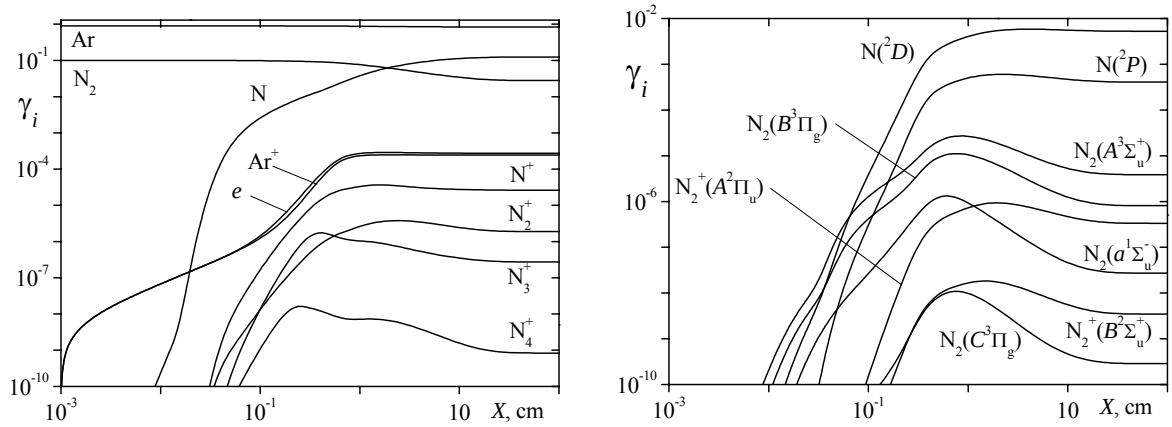

Fig. 3. Variation of species concentrations downstream the shock front in $N_2/Ar = 1/9$ mixture at $P_0 = 6$ torr, $T_0 = 300$ K and shock wave velocity $V = 3.4$ km/s.

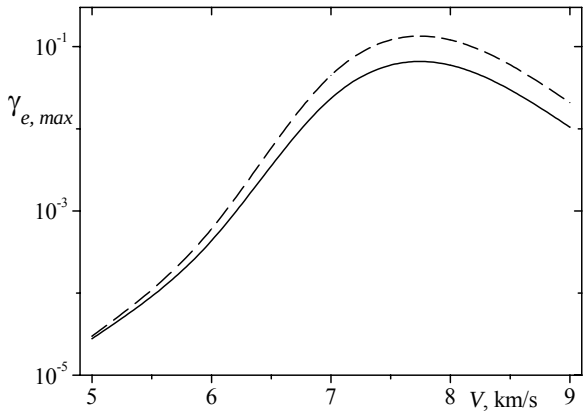

Fig. 4. Maximal value of electron mole fraction $\gamma_{e,max}$ as a function of shock wave velocity V predicted using two kinetic models: model involving electronically excited atoms and molecules (solid line) and model ignoring these particles (dashed line).

4 Acknowledgements

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